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NITRIFICATION IN PULSED ADSORPTION BEDS

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ABSTRACT

The Pulsed Adsorption Bed (PAB) is a tertiary wastewater treatment process which has shown excellent organic removal in laboratory and field studies.

Several indications in the initial studies pointed towards the feasibility of nitrification with the PAB process. A pilot plant study was conducted to obtain information about the nitrification effect of the process under various hydraulic and organic loads.

The results showed that the characteristics of the available sewage and the test set-up used did not allow significant nitrification. With other conditions favorable, an effective secondary treatment and solids retention times sufficiently high enough seem to be the strongest requirements to obtain nitrification.

Despite the failure of this study to demonstrate the possibility of nitrification, the excellent organic removal of the PAB process has been confirmed under different conditions and further studies should be able to optimize the PAB process for complete nitrogen removal.

NITRIFICATION IN PULSED ADSORPTION BEDS

1. INTRODUCTION

The goal for sewage treatment during the past three decades was removal of suspended matter and biochemical oxygen demand, plus reduction of bacterial contamination. The usual flow scheme for treatment facilities was plain sedimentation followed by biological treatment in activated sludge units or trickling filters, final sedimentation and eventually chlorination.

A large amount of research on the effect of waste discharge into natural water courses, demand for future increased water supply, as well as official and public concern about ecology have led to a demand for further waste treatment. This treatment is generally termed advanced or tertiary treatment. The purpose of advanced waste treatment is the further removal of carbonaceous matter resistant to classical biological treatment and additional removal of nitrogen and phosphorous. Nitrogenous material can exert appreciable oxygen demand and both elements are nutrients which enhance biological growth, or eutrophication in receiving water courses.

It should be noted that both the conventional activated sludge process and the standard rate trickling filters originally were designed to produce a highly nitrified effluent. The development of these processes came at a time when biological methods of measuring plant performances were yet unknown and chemical tests, especially tests for the different forms of nitrogen were used instead (1). When the BOD test,

measuring carbonaceous oxygen demand primarily, was introduced as standard for measuring plant performance, it was found that sufficient purification could be obtained to meet the standards without the long detention times necessary for nitrification. This resulted in several modifications of the biological processes.

Recent research has pointed towards the development of physical-chemical treatment processes and improvement of biological purification methods. One process which has gained much attention is adsorption of organic material onto granular media. This process combines both physical-chemical and biological activities. The media of choice is usually activated carbon, but other media like coal or sand are also nominal adsorbents, especially if biological activity is enhanced during the adsorption process.

Laboratory work on aerated adsorption columns by R. L. Johnson showed excellent organic removal from dilute wastes like secondary treatment effluents (2). The pulsing appearance of the media due to aeration gave the process its name, pulsed adsorption beds (PAB). A pilot plant study by S. R. Sedgwick at the sewage treatment plant of Ames, Iowa confirmed the laboratory results (3).

The characteristics of the PAB process and data from the original studies (2,3,4) are indicating that appreciable nitrification might be obtained in the PAB process. The possibility of nitrification would increase the benefits of the process and its field of applicability.

To confirm these indications and to obtain data about the degree of nitrification under different conditions, a PAB pilot plant

study was conducted at the Bethlehem, Pennsylvania sewage treatment plant.

2. THEORETICAL ANALYSIS

2.1 ADSORPTION PHENOMENON

The principle of adsorption is usually expressed with the classical Gibbs equation (5)

$$\Gamma = - \frac{c}{R\theta} \frac{d\gamma}{dc} \qquad (1)$$

where Γ is the excess surface concentration as weight per unit area, c is the bulk concentration of the solute as weight per volume, γ is the surface tension of the solution, and R and θ are the universal gas constant and the absolute temperature, respectively.

Equation 1 indicates a surface concentration higher than the bulk concentration for solutes which decrease surface tension, because the relative change of surface tension with concentration has a negative value for these solutes. Most organic materials produce a decreased suface tension and, thus, tend to accumulate on surfaces (4). The Gibbs equation also indicates increasing excess surface concentration with increasing bulk concentration. However, the importance of adsorption in waste treatment is for further treatment of the dilute secondary effluents. For these waste effluents the increased concentration of foodstuff on solid surfaces provides a more amenable environment for organisms. This concentration effect indeed is quite sizable if sufficient surface is provided (4).

2.2 THE NITROGEN CYCLE

Nitrogen is an element of special interest to sanitary engineers since it is essential to the life processes of all organisms. In these processes nitrogen appears in many different forms with different electronic charges, following a certain scheme known as nitrogen cycle (Fig. 1). In some of the transformations of nitrogen the N-containing compound is used as a source of oxygen and in others the compound itself is oxidized to provide energy for synthesis reactions.

The vast reservoir of nitrogen is the atmosphere where it is contained in molecular form as nitrogen gas. During electrical storms large amounts of nitrogen are oxidized and washed out by rain as nitric acid, HNO_3.

Plants utilize nitrogen as fertilizer by assimilating nitrate or ammonia or in special cases by fixing nitrogen from the air, thus transforming inorganic nitrogen into organic nitrogen.

$$\left.\begin{array}{l} NO_3^- + CO_2 + \text{green plants} + \text{sunlight} \\ NH_3 + CO_2 + \text{green plants} + \text{sunlight} \\ N_2 + \text{special bacteria or algae (blue-green)} \end{array}\right\} \rightarrow \begin{array}{l}\text{plant} \\ \text{protein}\end{array} \qquad (2)$$

Animals and humans, unable to utilize inorganic nitrogen, use the plant protein or other animal protein to produce own proteins.

Organic nitrogen is discharged upon death of organisms and in their waste products, fecal matter and urine. The released organic matter comes back into the soil, is washed out into water courses, or goes into sewer systems and into waste treatment facilities. The proteins

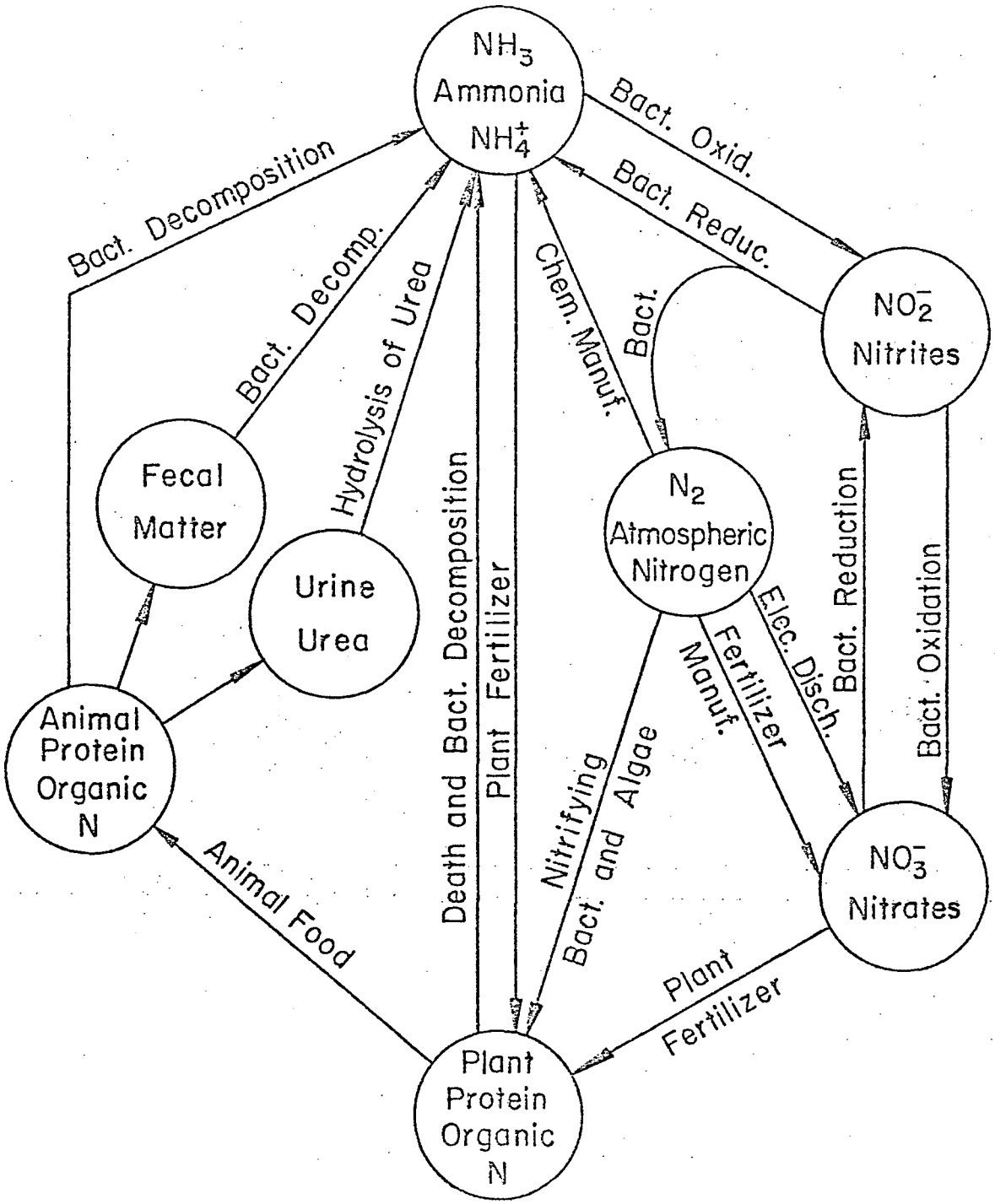


Fig. 1 Nitrogen Cycle

are readily transformed to ammonia by saprophytic bacteria under aerobic or anaerobic conditions.

$$\text{Protein} + \text{bacteria} \rightarrow NH_3 \quad (3)$$

The nitrogen in urine is largely contained as urea which is rapidly hydrolyzed to ammonium carbonate.

$$\begin{array}{l} NH_2 \\ | \\ C = O \\ | \\ NH_2 \end{array} + 2H_2O \xrightarrow{\text{urease}} (NH_4)_2CO_3 \quad (4)$$

The ammonia released may be used by plants directly and the excess ammonia is oxidized to nitrate by nitrifying bacteria. However, there is a larger number of bacteria capable of using organic nitrogen than capable of using NH_4^+, while even fewer bacteria can utilize NO_3^- for cell synthesis (6).

Nitrate finally can again be used as plant nutrient or it is reduced to nitrogen gas under anaerobic conditions by a large number of microorganisms.

2.3 THE NITRIFICATION - DENITRIFICATION PROCESS

2.3.1 Nitrification

Autotrophic nitrification or, simply, nitrification is the term for the oxidation of ammonia to nitrite and further to nitrate by autotrophic organisms. These autotrophic organisms derive their energy from the oxidation of inorganic nitrogen in contrast to the oxidation of organic carbonaceous compounds (6) by heterotrophic organisms. In

addition a large number of heterotrophic organisms produce low concentrations of nitrite or nitrate from ammonia.

Nitrification occurs in two steps and involves a very limited number of autotrophs. Genera capable of oxidizing nitrite from ammonia are Nitrosomonas, Nitrosococcus, Nitrosospira, Nitrosocystis, and Nitrosogloea, with the first two genera being most active. Only two genera, Nitrobacter and Nitrocystis are able to oxidize nitrite to nitrate. The reactions involved are (7)

$$NH_3 + 3O_2 \xrightarrow{\text{bacteria}} NO_2^- + H^+ + H_2O$$
$$2NO_2^- + O_2 \xrightarrow{\text{bacteria}} 2NO_3^- \qquad (5)$$

The growth rate of the nitrifiers is very slow and the yield of cells per unit of energy source oxidized is low. Therefore it is very important to attain conditions for optimal growth and retention of the organisms. The nutritional requirements are carbon dioxide, ammonia or nitrite, and a minimum concentration of dissolved oxygen of about 2 mg/l for optimal rates of nitrification (8). Certain minerals also are known to be needed, such as magnesium, iron, calcium, copper and especially high concentrations of phosphate (6).

An appreciable effect on nitrification is exerted by temperature and pH conditions. Data given in the literature are diverging to some extent, but the optimum temperature range seems to be 20°C to 30°C and the pH optimum is given with values from 7.6 to 8.8 for Nitrosomonas and 7.8 and higher for Nitrobacter (1,6,8,9).

Nitrification is inhibited by heavy metals like chromium, nickel, and zinc at concentrations above 0.25 mg/l (6,8). Peptone, cyanate and chlorate also were found to be toxic. The toxic effect of cyanates became smaller with decreasing levels of dissolved oxygen and stimulation was observed at low concentration of oxygen (6). Light also is reported to be inhibitory to nitrification.

Domestic sewage provides an excellent resource of foodstuff for nitrifiers. The necessary amount of nitrite as energy source for Nitrobacter is produced by Nitrosomonas, which appears to be the rate determining step for nitrification (8). At high concentrations of organic carbon the heterotrophs are in strong competition with autotroph organisms. Ammonia in this case is more readily available to the heterotrophs than for Nitrosomans, which may inhibit nitrification. The alkalinity of the sewage is important for governing nitrification with respect to its pH requirements. For neutralizing the acids generated during nitrification approximately 7 mg/l of alkalinity is required for 1 mg/l nitrogen oxidized (6).

Perhaps the most important effect on nitrification in sewage treatment is exerted by the solids retention time. Since the growth rate of nitrifiers is extremely slow, solids retention times presently used in high rate biological treatment are too low to obtain sufficient nitrification. In order to obtain effective nitrification, the SRT, or as it is also called in the the literature, the sludge age, has to be greater than the growth rate of the nitrifying organisms. The minimum sludge age necessary to prevent wash out of the nitrifiers

seems to be 3.5 days (10). It should be noted, however, that in some pilot studies sludge ages up to 22 days were used (11).

2.3.2 Denitrification

Microorganisms can use nitrate in two ways, by assimilating into organic matter via ammonia, or by utilizing the oxygen of the nitrate compound to oxidize carbonaceous matter. This nitrate respiration is called denitrification if molecular nitrogen or nitrous oxide are formed as end products. Nitrogen respiration proceeds at a much faster rate than assimilation, thus the majority of nitrate is reduced, mainly to nitrogen gas. A large number of bacteria and fungi, both heterotrophic and autotrophic are capable of nitrate reduction. Most notable are the genera Micrococcus, Pseudomonas, Denitrobacillus, Spirillum, Bacillus, and Achromobacter (6). The complex reactions may be generalized as follows

$$C_xH_yO_z + NO_3^- \xrightarrow{\text{bacteria}} N_2\uparrow + CO_2 + H_2O \qquad (6)$$

At the alkaline pH conditions usually encountered in sewage, strictly anaerobic conditions are reported to be neccessary for nitrification. However, there are some indications in the literature about denitrification under aerobic conditions with alkaline pH (6, p. 402). For denitrification of highly nitrified sewage effluents, methanol usually is added to supply the carbonaceous foodstuff for the denitrifiers.

2.4 ASPECTS OF NITRIFICATION IN PAB-UNITS

It may be concluded from these theoretical facts that the

PAB process can provide satisfying nitrification under the following conditions:

1) secondary biological treatment effluents as influent to provide adequate feed for the nitrifiers with reduced concentration of carbonaceous matter.
2) sufficient air supply to maintain an effluent dissolved oxygen concentration of more than 2 mg/1.
3) solids retention time longer than 3.5 days, preferably around 7 days.
4) pH in the range between 7.8 and 8.5.
5) temperature between 20°C and 30°C.

Experiments were conducted on pilot PAB units to compare the nitrification effect under different conditions.

3. DESCRIPTION OF EXPERIMENT

3.1 TEST APPARATUS

The PAB pilot unit was set up at the Bethlehem sewage treatment plant. The plant is presently operating at its full capacity of 12.5 MGD. The treatment process consists of primary settling, high rate trickling filters, secondary settling, and effluent chlorination. Sludge and effluent are recirculated from the secondary clarifiers.

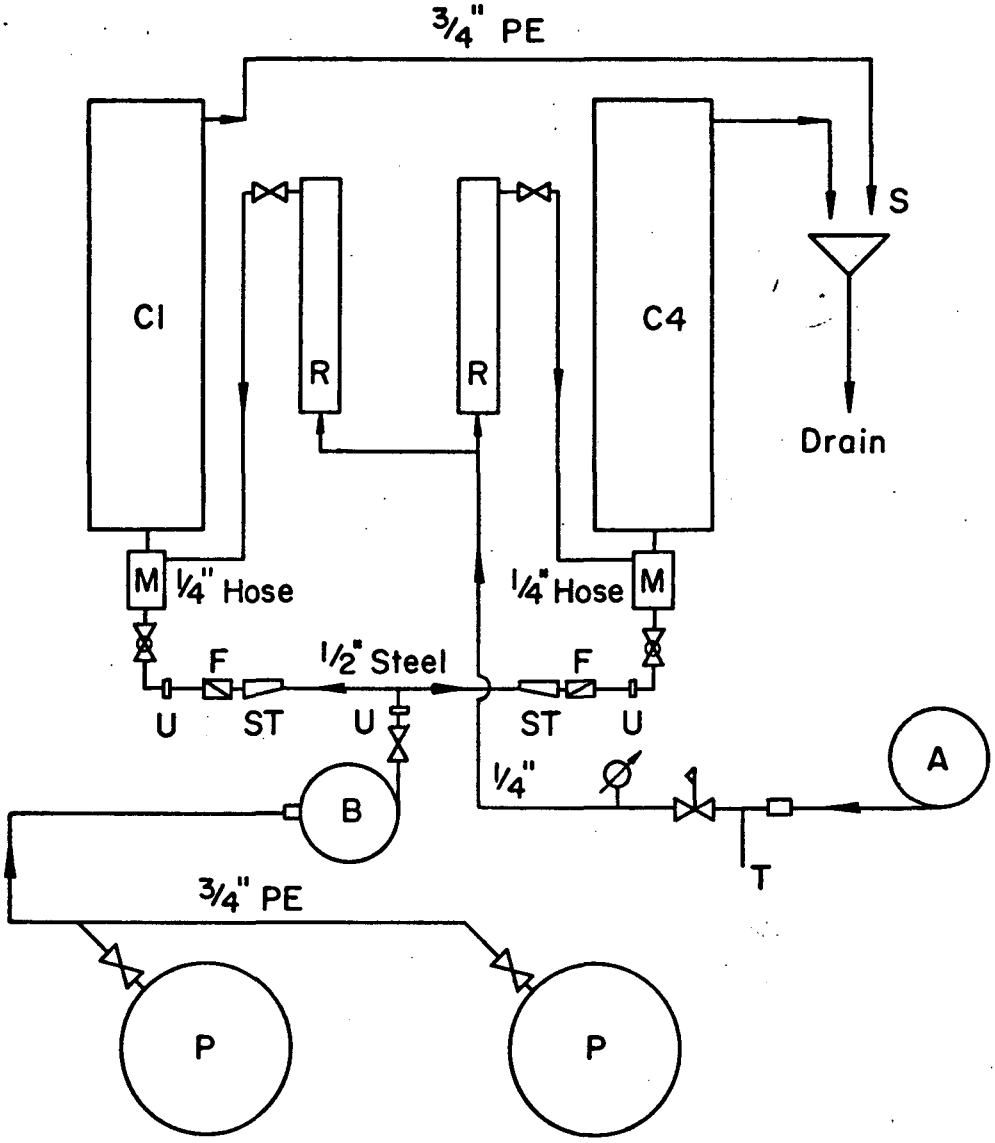
The PAB pilot unit was located in an inside room one floor above the pump room. It consisted of two 6 inch diameter 8 ft high columns with the necessary appurtenances for feed and air supply. The columns were numbered as PAB 1 and PAB 4 with respect to two additional columns which can be built between the existing ones. Secondary clarifier effluent recirculation was used as influent; the take-off

point was at the recirculation pumps in the pump room of the plant. The suction line was connected to two of the three recirculation pumps, to ensure continuous flow, since two of the three pumps were in operation alternately (Fig. 2). Gate valves were provided at the pump casing for operational safety. The material of the suction line was 3/4 inch polyethylene pipe. A booster pump[1] was used to provide sufficient pressure for flow control to the pilot units. A 3/4 inch ball valve was installed before the distribution line, followed by a union. The distribution line was 1/2 inch steel pipe and was connected to the mixing tube underneath the PAB columns. A flow control orifice[2] was installed in the distribution line to each PAB unit, preceded by a strainer and followed by a union. Another ball valve was installed just before the mixing tube. This arrangement of valves and unions in the distribution system provided for maximum operational flexibility and simple removal for maintenance and change of flow control orifices.

The columns were erected on a 1 ft high table. The mixing tubes were attached underneath the table. They were made of a 7 inch long piece of a 4 inch diameter PVC pipe with a bottom and a top plate (Fig. 3). The diffuser[3] was screwed through the plate of the table and reached about 6 inches into the mixing tube. The head of the diffuser had conical slots on its perimeter which converged to the outside to retain the filter media.

The columns used were adapted from an existing pilot sand filter with four 4 ft long filter columns, made of 6 inches diameter asbestos cement pipes. The two outside pipes were used as they were

1 1/2 HP. Teel Centrifugal Pump
2 Dole Flow Control, 1/2 gpm, 1/4 gpm
3 Media Retention Strainers by General Filter Company



A	Air Compressor	R	Rotameter
B	Booster Pump	S	Sampling
C	Pab - Columns	ST	Strainer
F	Flow Control	T	Trap
M	Mixing Tube	U	Union
P	Pump		

Fig. 2 General Piping Scheme

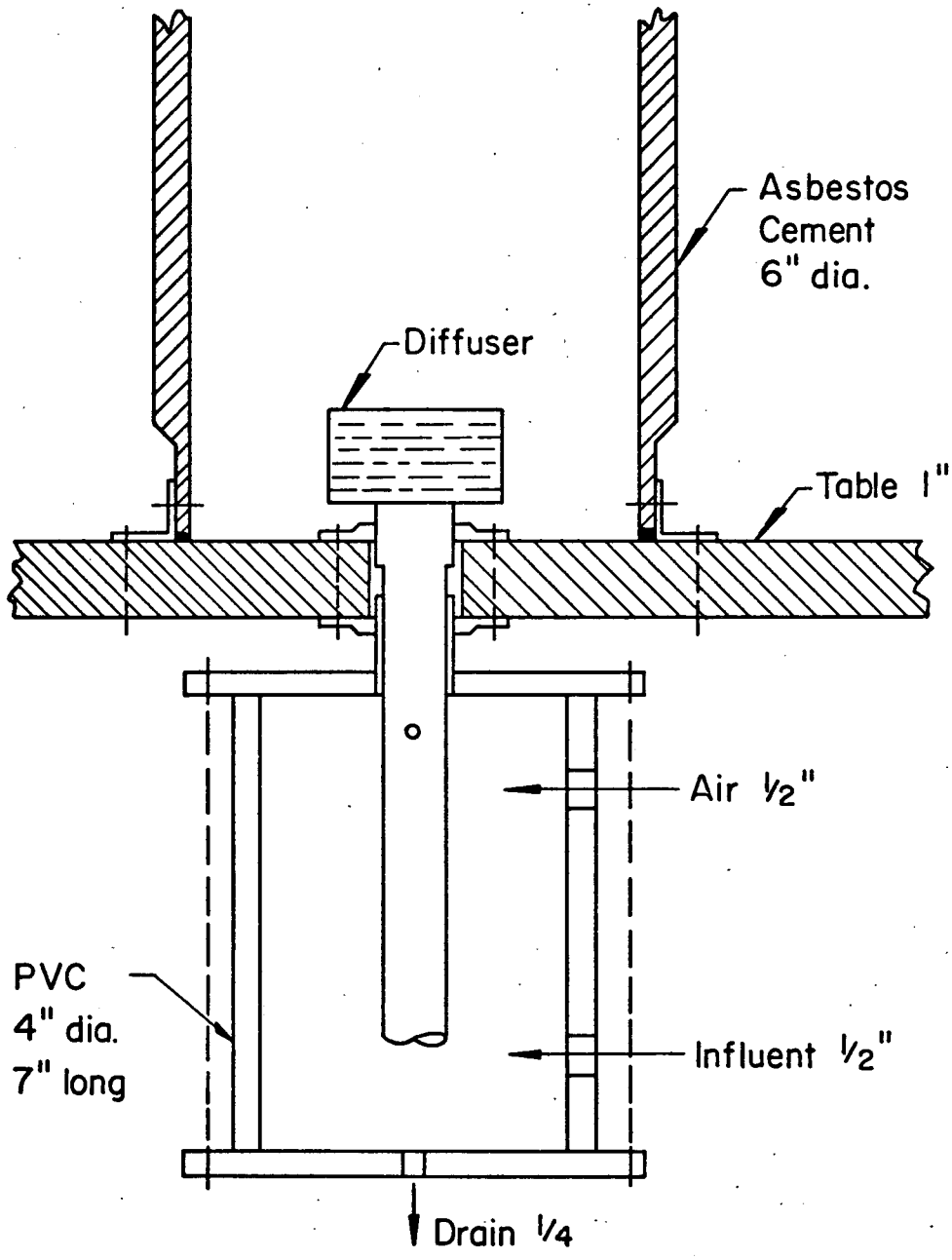


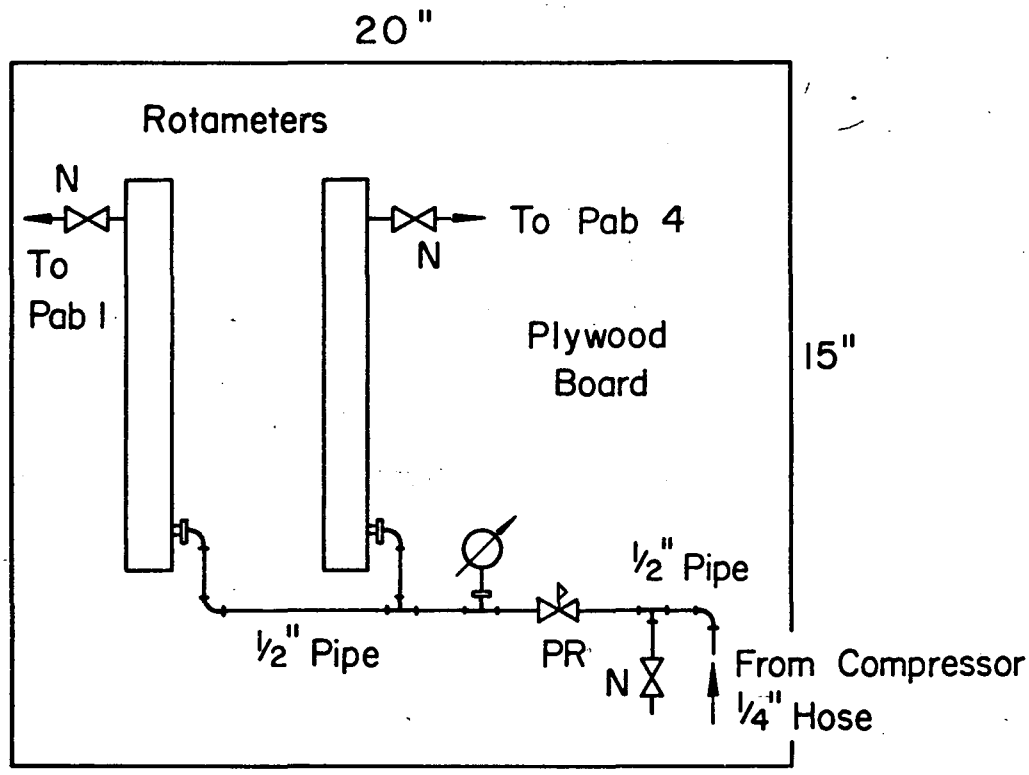
Fig. 3 Underdrain System

and the two inside pipes placed on top of the others to obtain the 8 ft long PAB columns. The problem of connecting the two pipes was finally solved by pulling a section of a tire inner-tube over the connections, which was first covered with epoxy glue. Four rings of banding material provided enough outside pressure on the connection. This provided a tight and flexible connection of the two pipe pieces. The upper pipe was secured in its position by tightening it to the wall. For the effluent a 1/2 inch nipple was tapped through the wall of the pipe, 6 inches from the top. A 3/4 inch polyethylene pipe conveyed the effluent to a funnel, where the samples were taken, and further down to the drain.

The air was supplied by a compressor[1] connected to the air flow control board (Fig. 4). Copper piping was used on the air flow control board and air hoses for the lines to and from the board. A trap, originally installed for condensate, was later equipped with a needle valve to release excess air to relieve the pressure relief valve on the compressor. The pressure regulator[2] was usually set at a constant outlet pressure of 10 to 12 psi. The air flow to each column was regulated with rotameters[3] equipped with a needle valve. The rotameter calibration curve is shown in Fig. 5. An additional needle valve was installed after the rotameters to allow shut off of the air line for maintenance work. An air hose connected the rotameter outlet to the mixing tubes.

The columns were filled 5 ft deep with sand as media. The sand had a mean diameter of 0.88 mm and 0.45 mm for PAB 1 and PAB 4,

1 1/4 HP Binks Compressor or 1/2 HP Bell and Gosset Compressor
2 Speedaire, No. 1Z838
3 Brooks Instrument Division, Rotameter, Model 1355, 150 mm scale, stainless steel float



N Needle Valve

PR Pressure Regulator

Fig. 4 Piping Scheme for Air Supply

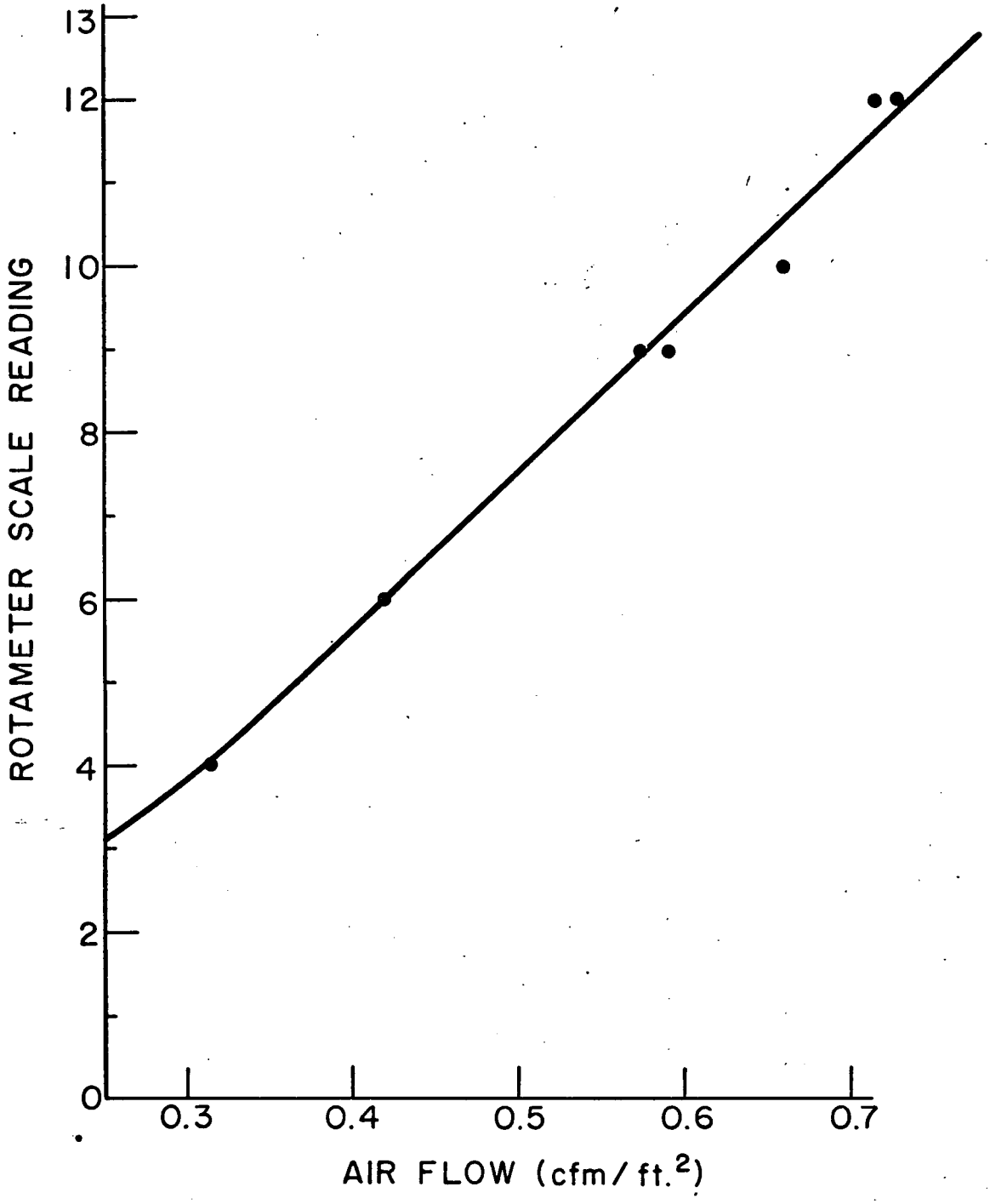


Fig. 5 Rotameter Calibration Curve

respectively. The grain size distribution of the sand is shown in Fig. 6.

Later in the study, the column PAB 1 was equipped with recirculation. The intake for the recirculation line was tapped through the column wall at the same height as the effluent, to which an elbow was added to provide a head of about 5 inches above the recirculation intake. Extreme care was taken to prevent sand to be washed into the recirculation line after breakdowns of the recirculation pump[1] had occured because of that reason. A tee with a plug at the bottom was attached to the intake to force the water to flow into the recirculation line from the top and to work as preliminary sand trap. A 12 inch piece of 5 1/2 inch diameter plexiglass tube was prepared as upflow clarifier before the recirculation pump. The discharge line with a second flow controller from the recirculation pump was connected to the distribution line to PAB 1.

3.2 EXPERIMENTAL ANALYSES

Several analyses were performed to monitor the performance of the PAB columns under different conditions. The sampling stations were the secondary clarifier recirculation box for the influent and the effluent lines on the pilot unit as shown in Fig. 2. Usually 8 hour composite samples were taken by the plant personnel during the day shift from 8 AM to 3 PM on weekdays. Of each hourly sample 90 ml were measured into a sample bottle, which also contained the previous samples of this day, and refrigerated at 5°C. In addition some grab samples were taken during the test period. The analyses

1 3/4 HP Teel Centrifugal Pump

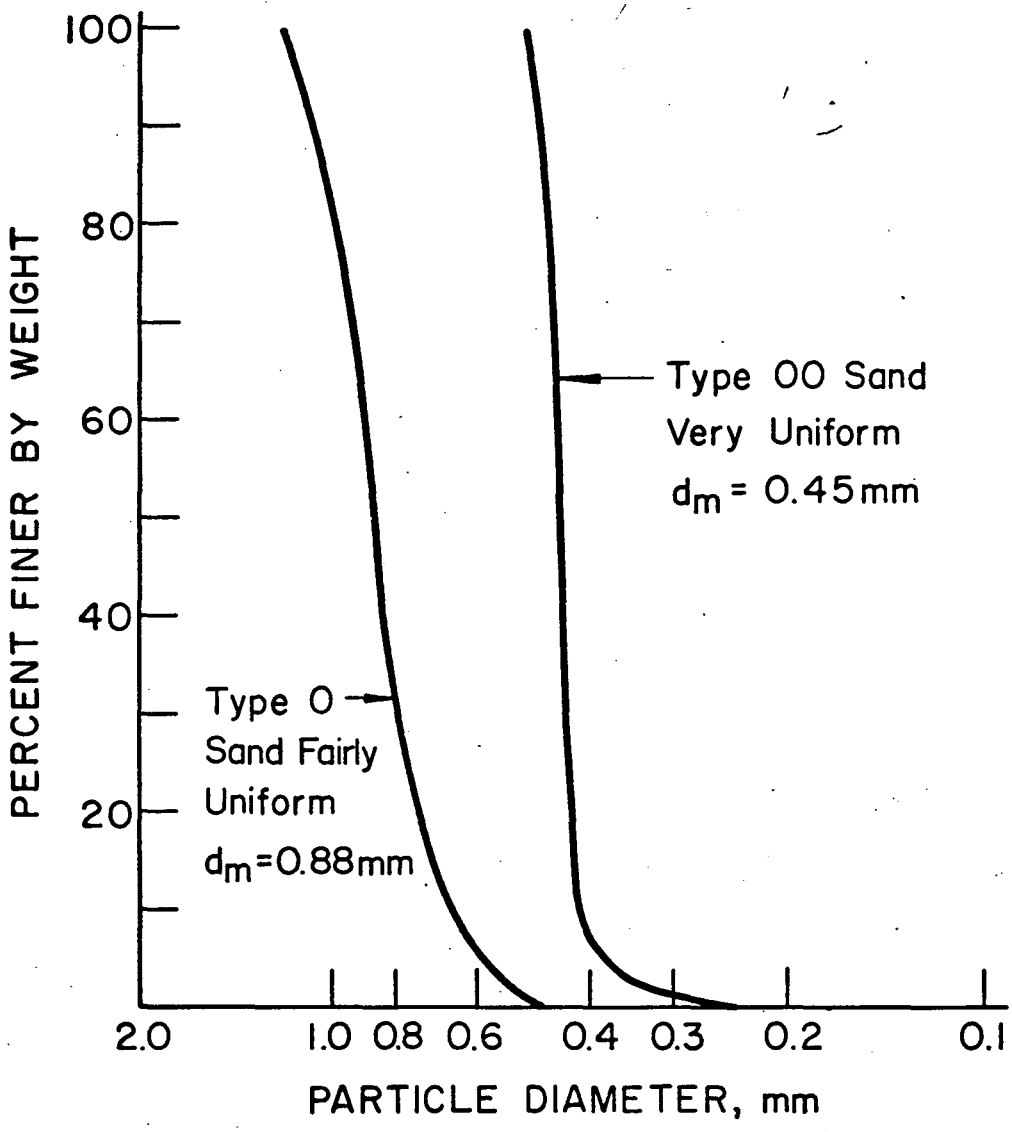


Fig. 6 Grain Size Distribution of Sand

were performed in the sanitary laboratory of Fritz Laboratory at Lehigh University.

The analyses performed on the daily samples were nitrogen forms, COD, solids determination and pH. BOD analyses were performed intermittently. The procedures used were as outlined in Standard Methods (12). Direct nesslerization was used for NH_4^+, diazotization for nitrite, the brucine method for nitrate and the glass filter method for solids determination. A spectrometer[1] was used for the colorimetric evaluation of the nitrogen tests. The standardization curves for NH_4^+-N, NO_2^--N, and NO_3^--N are shown in Fig. 7, 8, and 9. Samples of the media were taken from the top of the column beds to determine the amount of organic material on the media. Previous results have shown that the organic content is fairly uniform across the entire media depth, so that the sample from the top of the media was taken as representative (3). Approximately 250 ml of media were dried in an oven at 105°C for 24 hours and afterwards burned at 550°C for 1 hour. The weight difference before and after burning was taken as the weight of the organic material.

Tests performed directly at the pilot unit included measurements of the hydraulic rate, temperature measurements of air, influent, and effluents and measurements of headloss. For the last test a pressure gauge was connected to the drain valve of the mixing tube and the pressure reading was recorded.

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1 Bausch and Lomb Spectronic 20

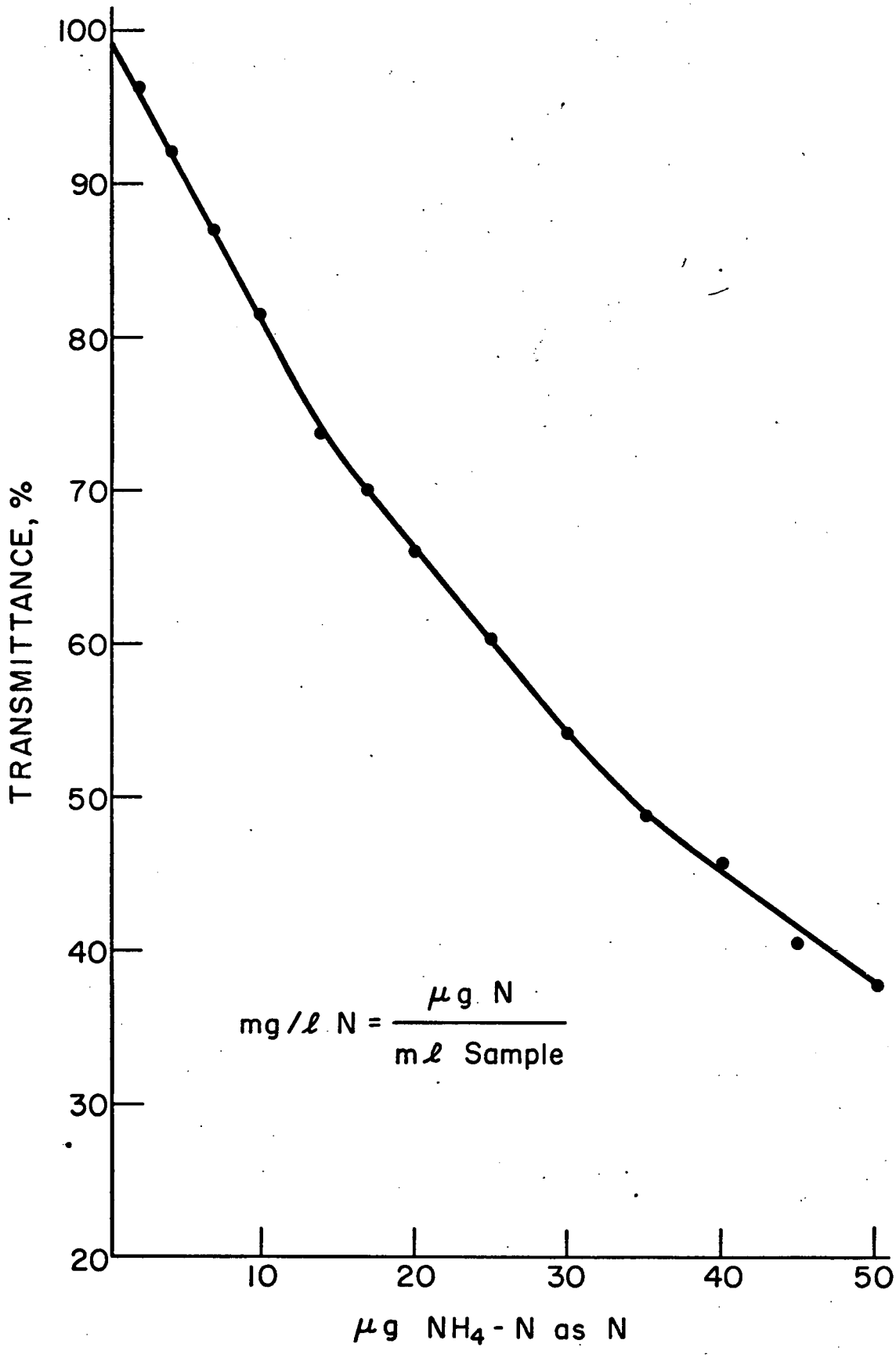

Fig. 7 NH_4^+ Standardization Curve

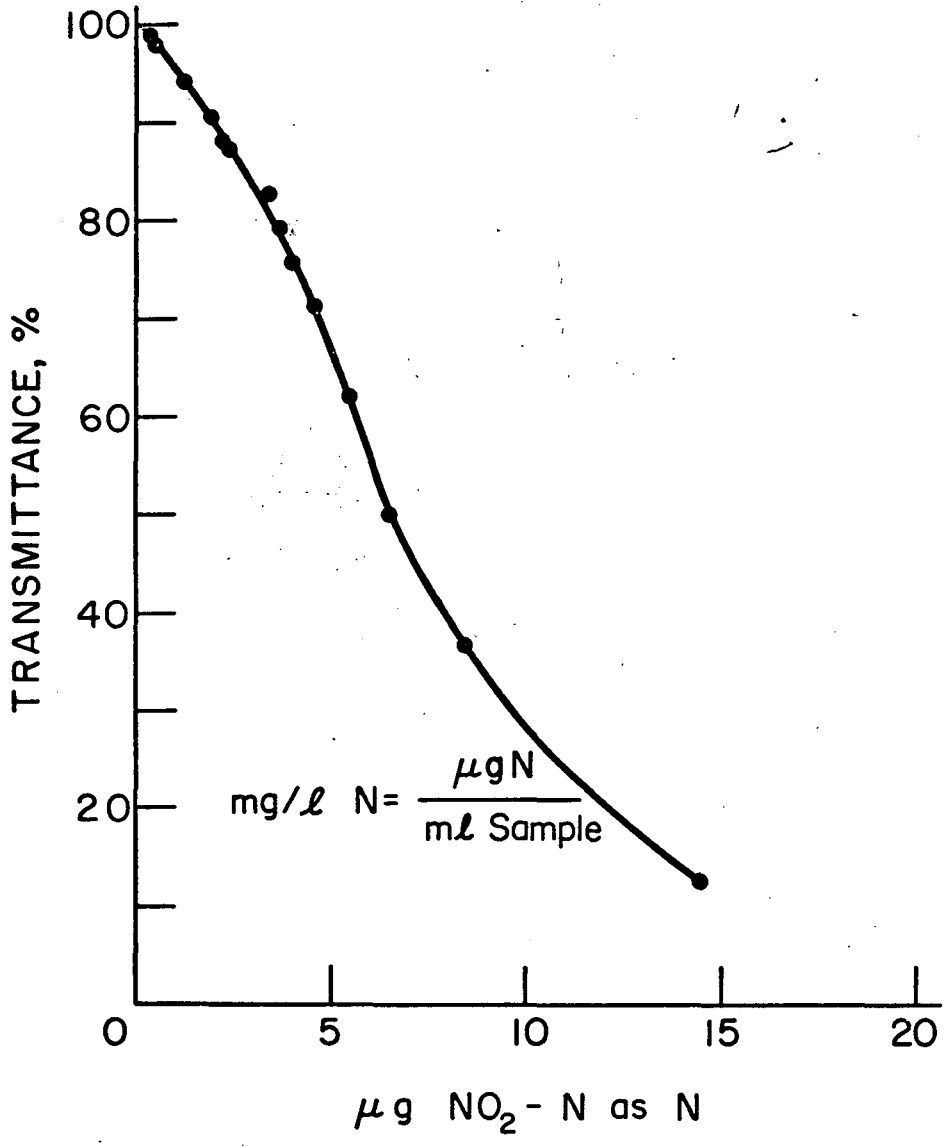

Fig. 8 NO_2^--Standardization Curve

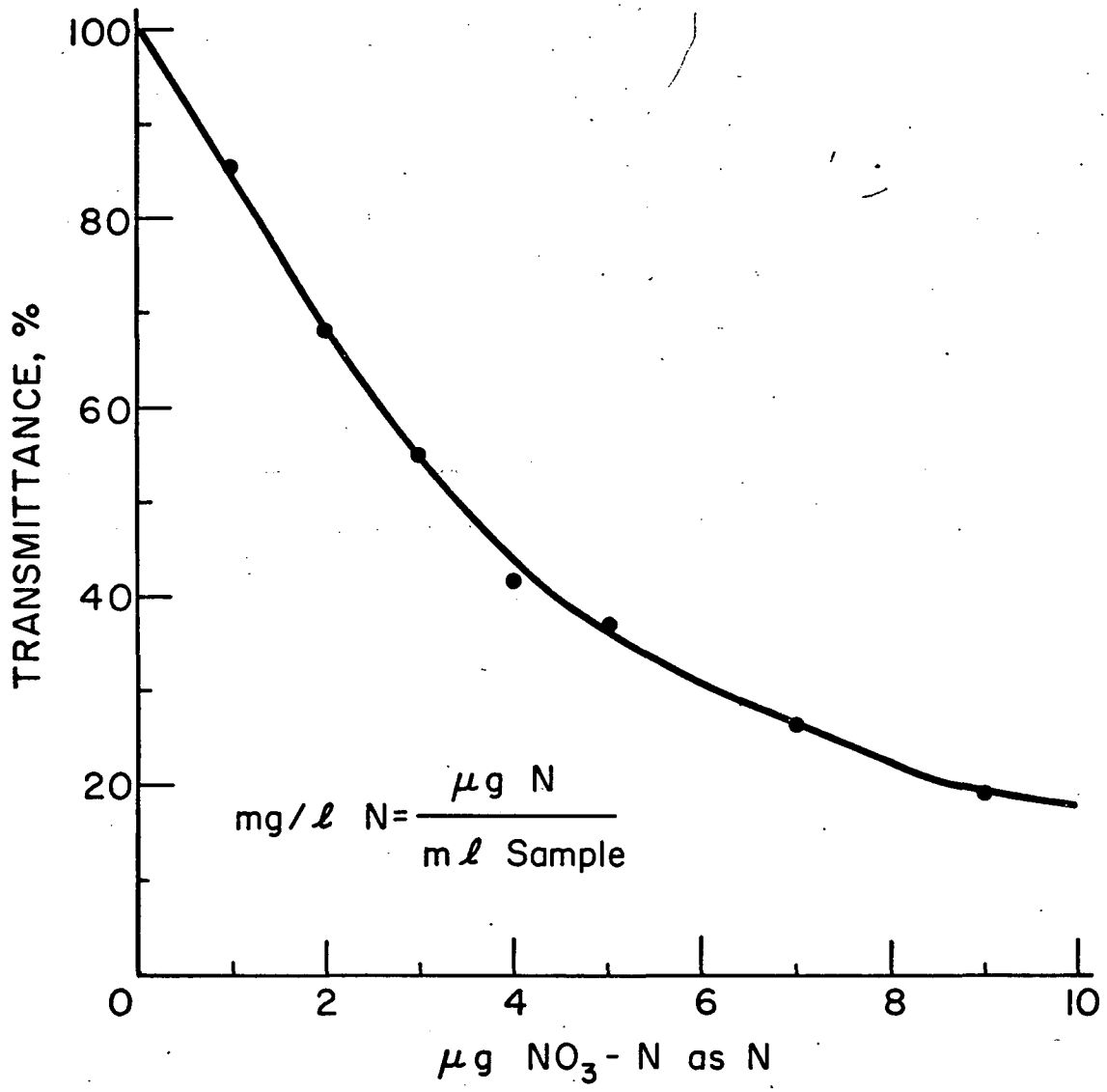

Fig. 9 NO_3^- - Standardization Curve

4. TEST RESULTS

The study can be divided into five stages with respect to changes in the main variables, waste flow and air rate. The conditions for these stages are shown in Table 1.

TABLE 1: Test Variables

Stage	Dates Operated	Waste Flow gpm/sq ft		Air Rate cfm/sq ft	
		PAB 1	PAB 4	PAB 1	PAB 4
1	10/6-10/20	2.5	2.5	0.7[a]	0.7[a]
2	10/20-11/1	2.5	2.5	0.4[b]	0.4[b]
3	11/1-12/1	2.5	1.75	0.6[b]	0.4[b]
4	12/1-12/8	1.75	1.75	0.73	0.68
5	12/22-1/6	1.75[c]	2.5	0.275	0.0

[a] estimated

[b] air rates unstable

[c] plus 1:1 recirculation flow

The operation of Stage 1 started with fresh sand in the columns. The hydraulic load was 2.5 gpm/sq ft (1.70 l/sec-m^2) whereas the air rate was still uncontrolled since the rotameters were not yet installed. From comparison with the appearance of the water surface on top of the columns during later stages, the air rate during Stage 1 was estimated with 0.7 cfm/sq ft (3.5 l/sec-m^2).

Little nitrification occurred, which might be explained by the slow growth rate of the nitrifiers together with the high air rate which might have washed out part of the organisms. The COD removal

averaged 33.4% for PAB 1 and 28.3% for PAB 4, at an average influent COD concentration of 137.8 mg/1. The complete list of results is shown in Appendix A. The pH increase across the units was consistently about 0.2 .

The installation of the rotameters marked the beginning of Stage 2. The hydraulic load remained the same as in Stage 1, but the air rate was reduced to 0.4 cfm/sq ft (2.00 l/sec-m^2). The operation during this stage had difficulties in the air supply system. The air rate to the units was controlled by the rotameters and excess air was released through the pressure relief valve on the compressor. This relief valve released increasingly more air, resulting in decreasing air supply to the columns. Several compressors of the same type were tried with unsatisfactory results. It should be noted, however, that all the compressors had been in use before for an unknown time, mainly for spraying purposes.

The NH_4^+-N concentration slightly increased across the columns, averaging 24.8 mg/1, 26.9 mg/1, and 26.5 mg/1 for influent, effluent PAB 1, and effluent PAB 4, respectively. At the same time the concentration of nitrate nitrogen was decreasing from 0.43 mg/1 average in the influent to 0.21 mg/1 in the effluent of PAB 1 and 0.26 mg/1 in the effluent of PAB 4. The COD reduction during Stage 2 averaged 22.7% for PAB 1 and 10.2% for PAB 4, with average influent concentration of 114.3 mg/1 COD. The pH increase of effluent over influent during Stage 2 was only about 0.1 units. The summary of the results of Stage 2 is given in Appendix B.

During Stage 3 the unit PAB 1 was operated with the same hydraulic rate but with an air rate of 0.6 cfm/sq ft (3.0 1/sec-m^2), whereas the hydraulic rate for PAB 4 was cut down to 1.75 gpm/sq ft (1.19 1/sec-m^2) at the same air rate as in Stage 2. Volumetric measurements showed that the actual flow rate of the flow controller was 0.35 gpm, 40% above the nominal rated flow rate of 0.25 gpm. The ammonia level again was almost the same for influent and effluents. The COD removal increased to 31.3% for PAB 1 and to 28.0% for PAB 4 at an average influent concentration of 127.0 mg/1.

The problem with decreasing air rates were partially solved during this stage when another air compressor was installed, which had undergone extensive repair. In addition the air system was cleaned thoroughly from condensated water vapor and solids particles.

In Stage 4 the hydraulic rate to both units was 1.75 gpm/sq ft (1.19 1/sec-m^2) the air rate to PAB 1 was 0.73 cfm/sq ft (3.65 1/sec-m^2) and to PAB 4 it was 0.68 cfm/sq ft (3.40 1/sec-m^2). The air rates remained constant throughout this stage. On the first day of this operation sampling of the media to determine organic content was started. On this occasion the can used for sampling was pushed into the sand of PAB 1 and broke from the handle lodging in the media bed. Immediate attempts to get the can out were unsuccessful since it rapidly moved down through the media. The results of Stage 4 are tabulated in Appendix D.

At the end of Stage 4 some plugging in PAB 1 was indicated by increasing head loss and difficulties with media sampling. The

media was consequently stirred to dislocate plugged layers. Especially around the diffuser head some hard layers were noticed. Two days later most of the media was thrown out of the column PAB 1, due to the violent agitation of the airflow in the partially clogged column. This unit was consequently completely overhauled in order to be equipped with recirculation for Stage 5. This unit was chosen for the operation with reciruclation since it had shown better results in the previous stages.

After several unsuccessful attempts it was finally possible to remove the lost sampling can from the column, not without emptying the column almost completely. A new air compressor was installed, the air lines thoroughly cleaned and the trap in the air line was equipped with a release valve for excess air. Finally the unit again was filled with 0.88 mm sand.

Recirculation on PAB 1 was actually installed prior to the removal of the can. A second overflow of media and resulting damage of the seal on the recirculation pump finally urged the removal of this can. Since no further difficulties occurred with media being thrown out of the columns, these problems obviously were due to the obstruction in the flow by the presence of this can. The resulting higher velocities around the can obviously lifted the media above it and eventually threw it out of the column. Furthermore, a sand trap was built in the recirculation line to prevent future pump damages by sand particles.

After this Stage 5 started with fresh media and recirculation on PAB 1. The other unit was running without air supply under

almost anaerobic conditions during this stage. However, tests were conducted almost exclusively on PAB 1.

The start-up conditions gave interesting results which are shown in Appendix E and in Fig. 10, 11. The air rate was initially set at 0.365 cfm/sq ft (1.80 l/sec-m^2), but later lowered to 0.275 cfm/sq ft (1.38 l/sec-m^2) since the dissolved oxygen concentration with the initial air rate was unnecessarily high.

5. DISCUSSION

5.1 DISCUSSION OF TEST RESULTS

The principal result of the experiment is that it was not possible to obtain nitrification under the given circumstances. It was shown during all five stages that neither lowering the hydraulic rate nor changes of the air rate had an effect on nitrification. Even recirculation did not improve the conditions. It is rather difficult to detect the source of this failure without additional intensive investigations, but some indications can be derived from theoretical considerations.

It has been shown that nitrification is mainly dependent on five conditions:

1) Solids retention time longer than the growth rate of the nitrifiers
2) Low concentrations of carbonaceous matter
3) Absence of inhibitory or toxic elements like heavy metals, cyanides, or phenol
4) Temperature in the range of 20°C to 30°C

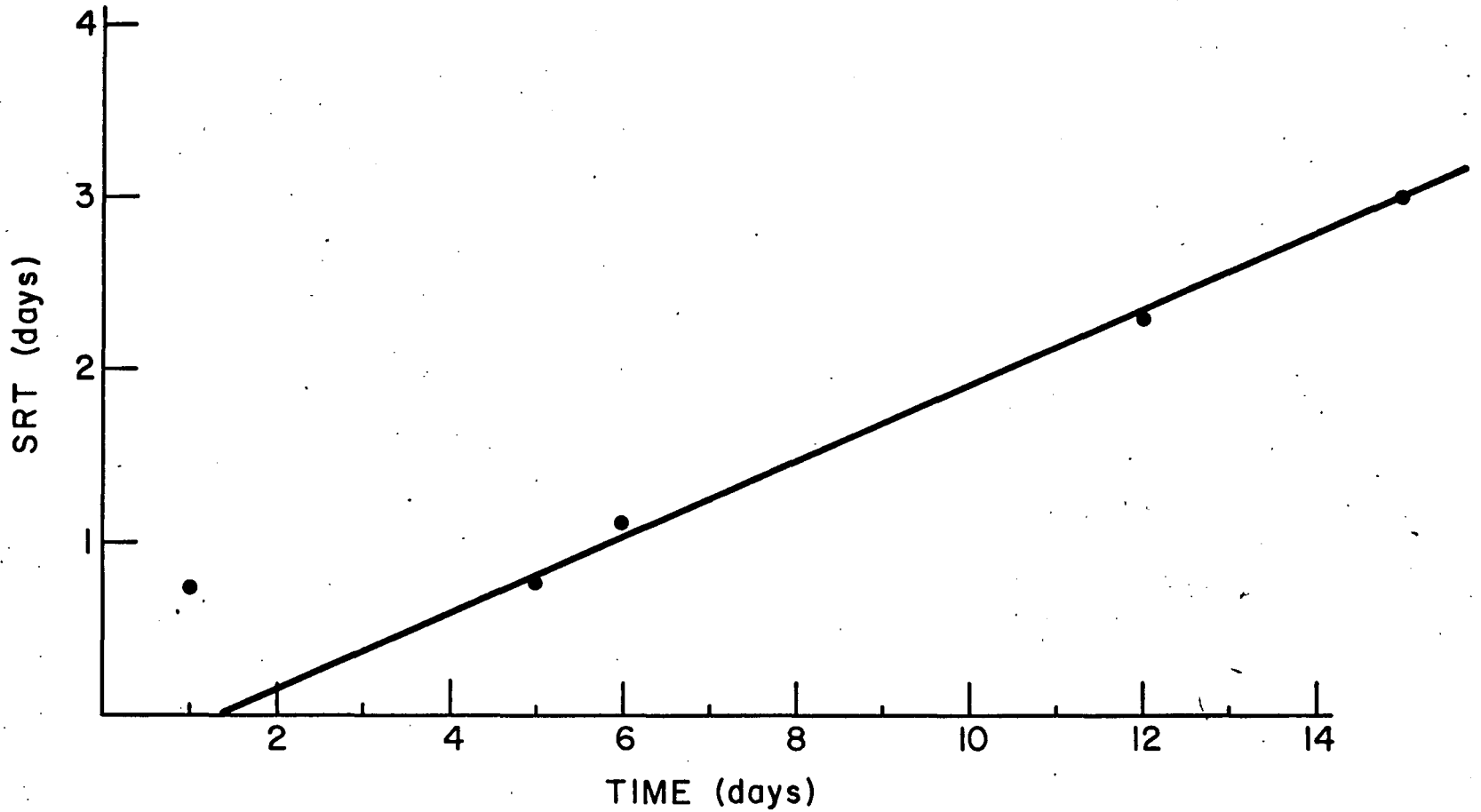

Fig. 10 SRT - Start-Up Curve

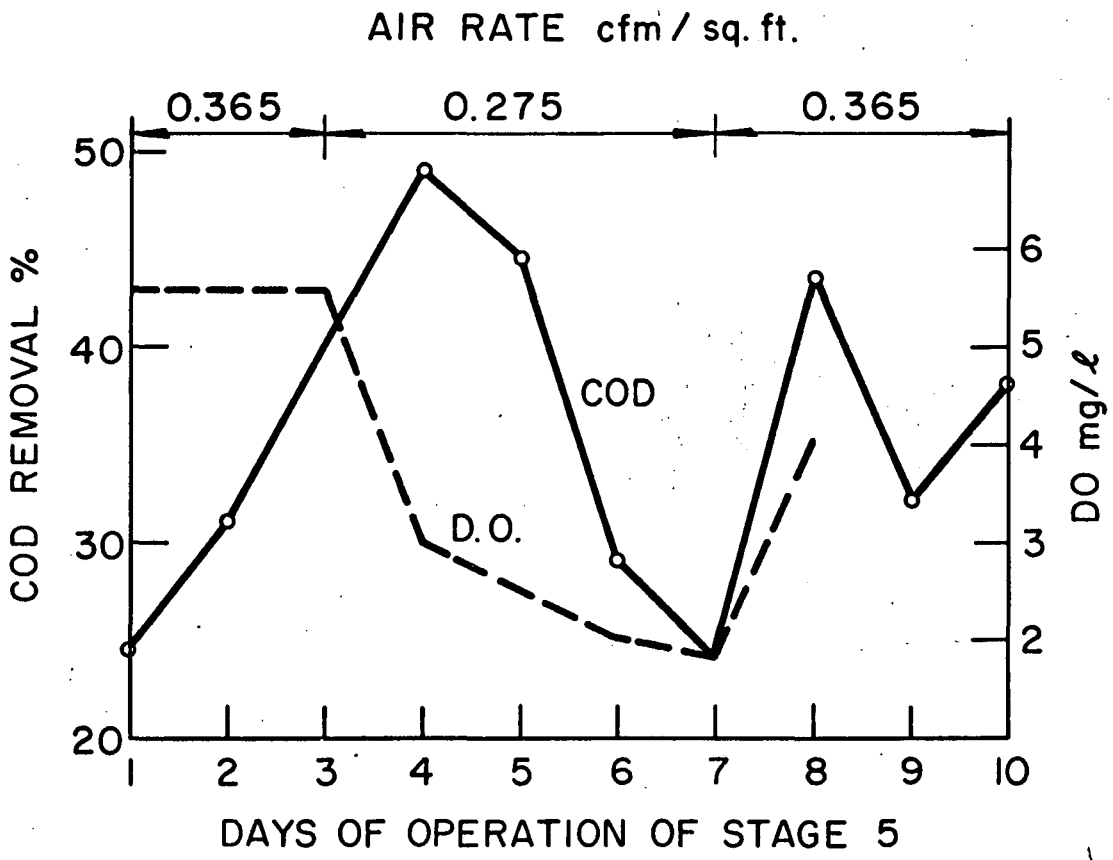

Fig. 11 COD Removal and D.O. Concentration Versus Time

5) pH above 7.8, preferably around 8.5

The solids retention times given with the results in the appendices show at least for the unit PAB 1 in Stage 4 and for PAB 4 in Stage 3 and Stage 4 a value larger than 3.5, the minimum usually specified in the literature. The start up curve for Stage 5 (Fig. 10) also shows a rapid increase of SRT above the minimum level. Since the organic mass adsorbed onto the media is fairly constant for a continuous operation, average values of SRT can be computed for the different stages (Table 2).

TABLE 2: AVERAGE SOLIDS RETENTION TIMES[a]

		Organic Mass	VSS Wasted		SRT	
Stage	PAB	In PAB Units g	Avg. g/day	Range g/day	Avg. days	Range days
3	1	87.8	24.7	17/35	3.6	2.5/5.2
	4	93.2	21.5	13/31	4.3	3.0/7.2
4	1	84.3	19.8	12/24	4.3	3.5/7.0
	4	88.0	19.7	17/22	4.5	4.0/5.2
5	1	88.3	29.0	22/35	3.1	2.5/4.0

[a]Blank correction: 23.2g

The values for organic mass in the units in Table 2 are corrected by a blank for loss of weight for the clean sand during burning. The average SRT was slightly above the minimum value of 3.5 during Stage 3 and 4. However, the SRT values shown are not corrected for the percentage of inactive organic mass. The fraction of inactive organic mass in the units is most probably higher than in the effluent. The SRT

values in Table 2 are therefore higher than the actual value. Thus it seems likely that nitrifiers were washed out to some extent, which might have inhibited nitrification.

The requirement of a low concentration of carbonaceous matter in the influent certainly is very important. This requirement implies pretreatment of the sewage by an effective secondary stage which should not only provide an effluent with low COD or BOD but also an almost complete breakdown of organic nitrogen to ammonia. High organic carbon concentrations might be toxic to nitrifiers (8) and incomplete conversion of organic nitrogen to ammonia imposes an additional load on the nitrification step.

The secondary clarifier effluent which was used as influent for the pilot units had COD values which were generally higher than usual values for effluents of secondary biological treatment plants (see appendices). The average of all COD values for the pilot influent was 136.4 mg/l, extremely high if compared with usual values for plant effluents of 40 mg/l to 60 mg/l COD. Of special interest was the COD: BOD ratio of the influent with an average of roughly 4:1 (Fig. 12). This indicates either the presence of inhibitory or toxic materials or a very poorly biodegradable sewage. Periodically higher concentrations of cyanide were reported by the plant laboratory during the test period. However, more results would be necessary about toxic or inhibitory contaminants to allow definite conclusions. In the case of unusually high concentrations of cyanide or metals, it is quite obvious that nitrification would be hindered considerably since the nitrifying bacteria

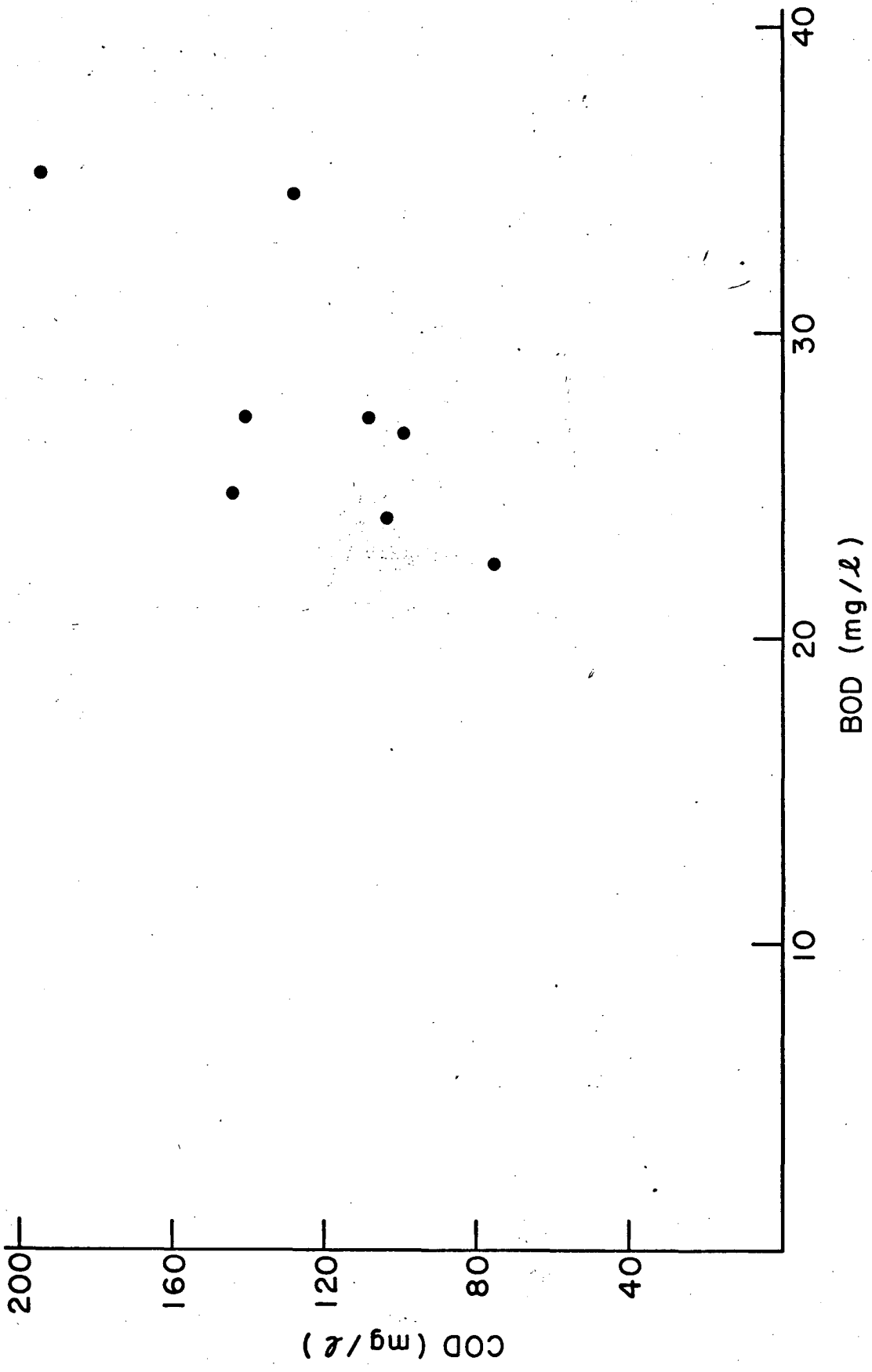

Fig. 12 COD-BOD Relation

are even more sensitive to inhibitors than others.

Interference with nitrification by adverse conditions of temperature or pH is not probable in this case. Influent temperature was never lower than 13°C with an effluent temperature essentially constant at 21°C. Likewise pH values were in a fairly good range with a low of 7.15 and an average of 7.5.

The only plausible explanation for the decreasing nitrate levels across the pilot unit is denitrification. This result is in strong contradiction to the general theory. A strict requirement for denitrification is anaerobic condition. Only a few reports have been made about possible denitrification at concentrations of dissolved oxygen up to 0.5 mg/l. The DO concentrations usually were at levels above 2.0 mg/l during the entire study. However, the nitrate concentrations removed were very small. It seems from these results that aerobic conditions are not toxic to denitrifying bacteria, although the rate of denitrification seems to be greatly reduced.

The nitrogen tests performed failed to account for organic nitrogen, the usual Kjeldahl test for organic nitrogen could not be performed since there was no equipment available. The high COD concentrations of the PAB influent indicate a relatively poor biodegradation with incomplete transformation of organic nitrogen to ammonia. Effluent ammonia concentrations slightly higher than the influent value confirm the occurrence of further conversion of organic nitrogen to ammonia in the PAB units. On the other hand, some data indicate effluent ammonia concentrations lower than the influent value which would mean

that there is some nitrification taking place, which in turn might be carried further to denitrification. However, the relative change of ammonia concentration between influent and effluent normally was very small, actually smaller than the accuracy obtainable with the test procedure (12). Any definite conclusions in this respect are therefore impossible.

The obtained results of organic removal confirm the previous studies (3,4). The removal efficiency of the PAB process is much higher than in other biological treatment processes, if weight removed per unit volume is considered. The high removal efficiency is obtained by the high organic loading possible in the PAB process, which is a definite economic advantage. Removal efficiencies for several secondary biological treatment processes and the PAB process are shown in Table 3.

TABLE 3: BOD Removal in Biological Treatment Processes

Process	Loading		Removal
	lbs BOD_5/1000 ft^3-day	%	lbs BOD_5/1000 ft^3-day
Activated Sludge			
Conventional	35	90	31.5
High Rate	100	60	60
Trickling Filter			
Conventional	15	80	12
High Rate	60	65	42
PAB[a]	150	60	90

[a] based on: influent BOD_5 = 25 mg/l; Q = 2.5 gpm/ sq ft; media depth H = 5 ft

The performance of the unit PAB 1 with coarser media was generally superior to the performance of PAB 4 with the finer media. It can be seen from the data of Stage 2 and Stage 3, that especially at low DO concentrations the organic removal is better with coarse media. Reducing the flow rate from 2.5 gpm/sq ft to 1.75 gpm/sq ft increased the COD removal from 33.4% to 44.2%, comparing Stage 1 and Stage 4 with comparable air flow rates.

The great influence of a proper air rate on the performance of the PAB was demonstrated. When the rotameters were first installed, the air rate for both units was set at the upper limit recommended in the original study by R. L. Johnson (4), at 0.4 cfm/sq ft (2.00 l/sec-m^2). It soon became obvious that higher air rates were necessary for the conditions encountered in this study. Reducing the air rate from approximately 0.7 cfm/sq ft (3.5 l/sec-m^2) in Stage 2 also reduced the COD removal by about 16% for PAB 1 and 47% for PAB 4. The COD removal was highest with 44.2% in PAB 1 during Stage 4 with an air rate of 0.73 cfm/sq ft (3.65 l/sec-m^2). The demand for higher air rates was caused by the higher COD concentrations encountered in this study than in the original investigations at Ames, Iowa.

The influence of air rate and DO concentrations on COD removal can be seen best from the data of Stage 5. In Fig. 11, COD removal and DO concentration are plotted against time of operation. The air rate initially set at 0.365 cfm/sq ft (1.80 l/sec-m^2) resulted in a DO concentration of 5.6 mg/l. During this period the COD removal increased as more organics adsorbed onto the fresh media. Since this

DO level was unnecessarily high and some sand was washed out of the bed, the air rate was reduced to 0.275 cfm/sq ft (1.38 1/sec-m^2). Subsequently the COD removal dropped with gradually decreasing DO. When the air rate was reset at 0.365 cfm/sq ft, the COD removal suddenly increased again. From this it seems that a certain minimum air rate is necessary to maintain a constant level of DO. Another fact which is again confirmed by the data of Fig. 11 and also by Fig. 10 is the excellent ability of the PAB to recover after interruption of continuous operation. This is a great operational advantage.

The second reason for using air in the PAB is agitation of the media to prevent clogging. This agitation is caused by the upward flow of the sewage and the additional pulsing action of the rising and coalescing air bubbles. No problems whatsoever were encountered with PAB 4 with the 0.45 mm media. The media seemed to be slightly more expanded during operation than in static conditions. During Stage 5 when PAB 4 was operated without air feed, the media maintained the same state of slight expansion for almost two weeks, only on the last day of operation of Stage 5 a sudden increase in expansion by about 20% of the original volume was noticed. This rapid expansion probably was caused by increasing accumulation of organic material on the sand particles, thus decreasing their bulk density. However, a media sample which was taken on the last day of operation showed a lower concentration of organics in the media than expected (Appendix E). This possibility of anaerobic operation of the PAB columns is very interesting

and will be discussed later.

The conditions in PAB 1 were completely different. While it was failrly easy to take media samples at the 2.5 gpm/sq ft flow rate, it was quite difficult to push the sample can into the media at the lower flow rate of 1.75 gpm/sq ft. This indicates a distinct change in the condition of the bed. At the lower flow rate the bed obviously was almost packed despite the pulsing action of the air bubbles, whereas the increase of the flow rate caused a slight expansion. Operational difficulties may be expected with coarse media and low flow rates, unless the air rates are kept very high.

The constant increase of pH by about 0.1 to 0.2 units has some potential with respect to nitrification. With the great sensitivity of the nitrifiers to pH level, even a small increase in pH can result in greatly improved conditions for nitrification (1). For the pH variations during the test period, see Fig. 13.

The termperature data have to be analyzed with consideration of the location of the pilot units. Due to the indoor location the air temperature dropped only from 27°C to 24°C during the test period. This high air temperature certainly also influenced the sewage temperature. Of interest is the different effluent temperature during long periods (Fig. 14).

The measurements of headloss for the different conditions were evaluated with the modified friction term as given by R. L. Johnson (2, p. 1651) with $f(H/d)^2$, where f is the friction coefficient

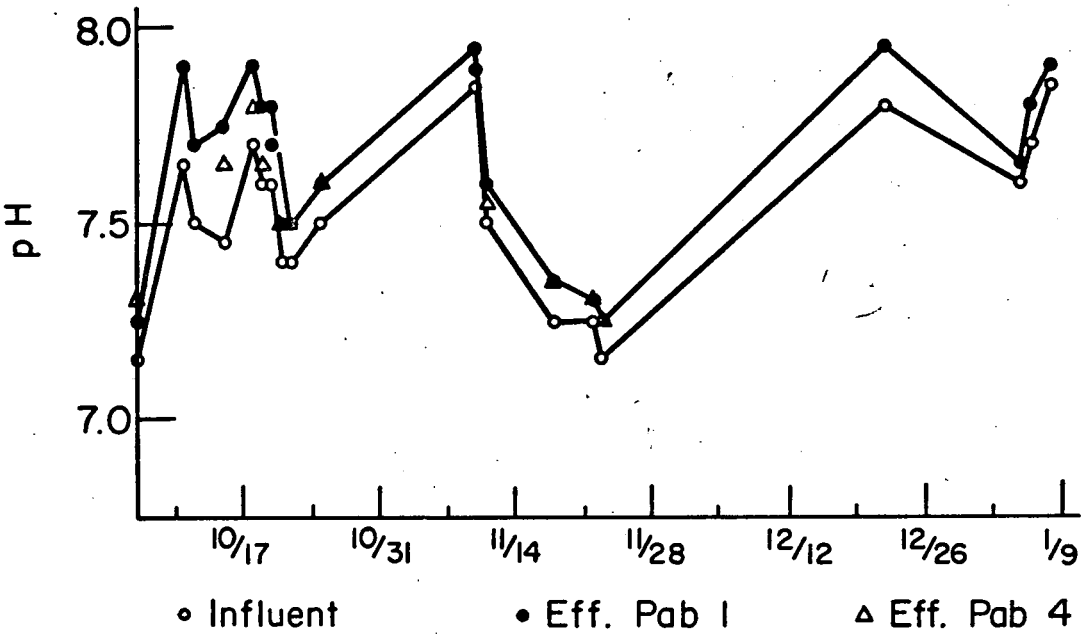

Fig. 13 pH Variation

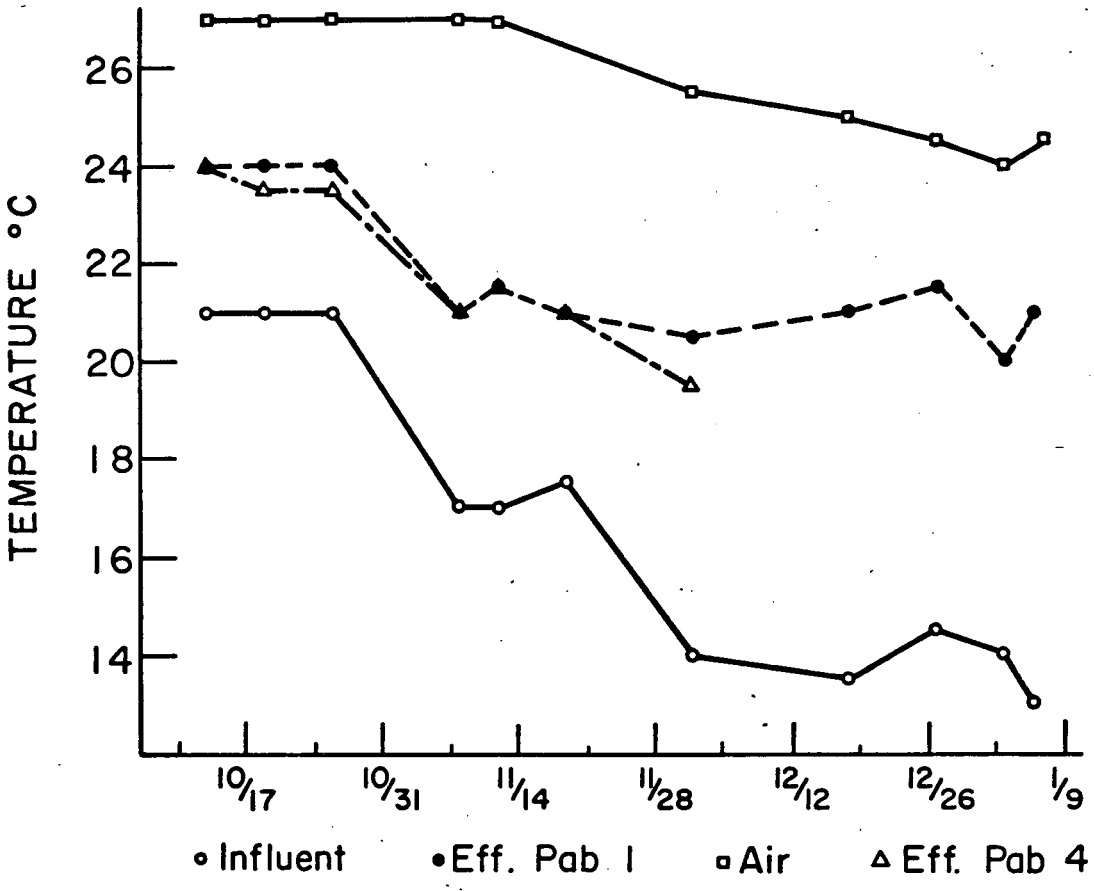

Fig. 14 Temperature Variation

of the Darcy-Weisbach formula, H is the media depth and d is the media diameter. This modified friction term was correlated with a modified Reynolds Number which is given by

$$R_m = \frac{vd}{\nu} + \frac{v_a\, d}{\nu_a} \qquad (7)$$

based on the approach velocities of waste and air. The results of this study and the correlation line of the original study are shown in Fig. 15. It should be noted that the headloss measurements of this study include diffuser loss, which is not included in the original study.

Quite surprising was the small effect of recirculation during Stage 5. Neither nitrification could be observed nor was the COD removal efficiency increased (Appendix E). However, the increased COD load due to decreasing performance of the plant trickling filters during the winter time and the short time of operation may be responsible for the lack of improvement by recirculation.

The data of solids concentration usually show a decrease across the PAB units. Higher solids concentrations in the effluent indicate that particles were washed out of the system which did occur periodically. The air rate and the bubble size have a definite influence on the sloughing action within the media bed. Excessive air rate and coarse bubbles should be avoided to minimize the sloughing action.

5.2 OPERATIONAL ANALYSIS

The biggest operational advantage of the PAB process is the possibility of continuous operation without backwashing. But there are

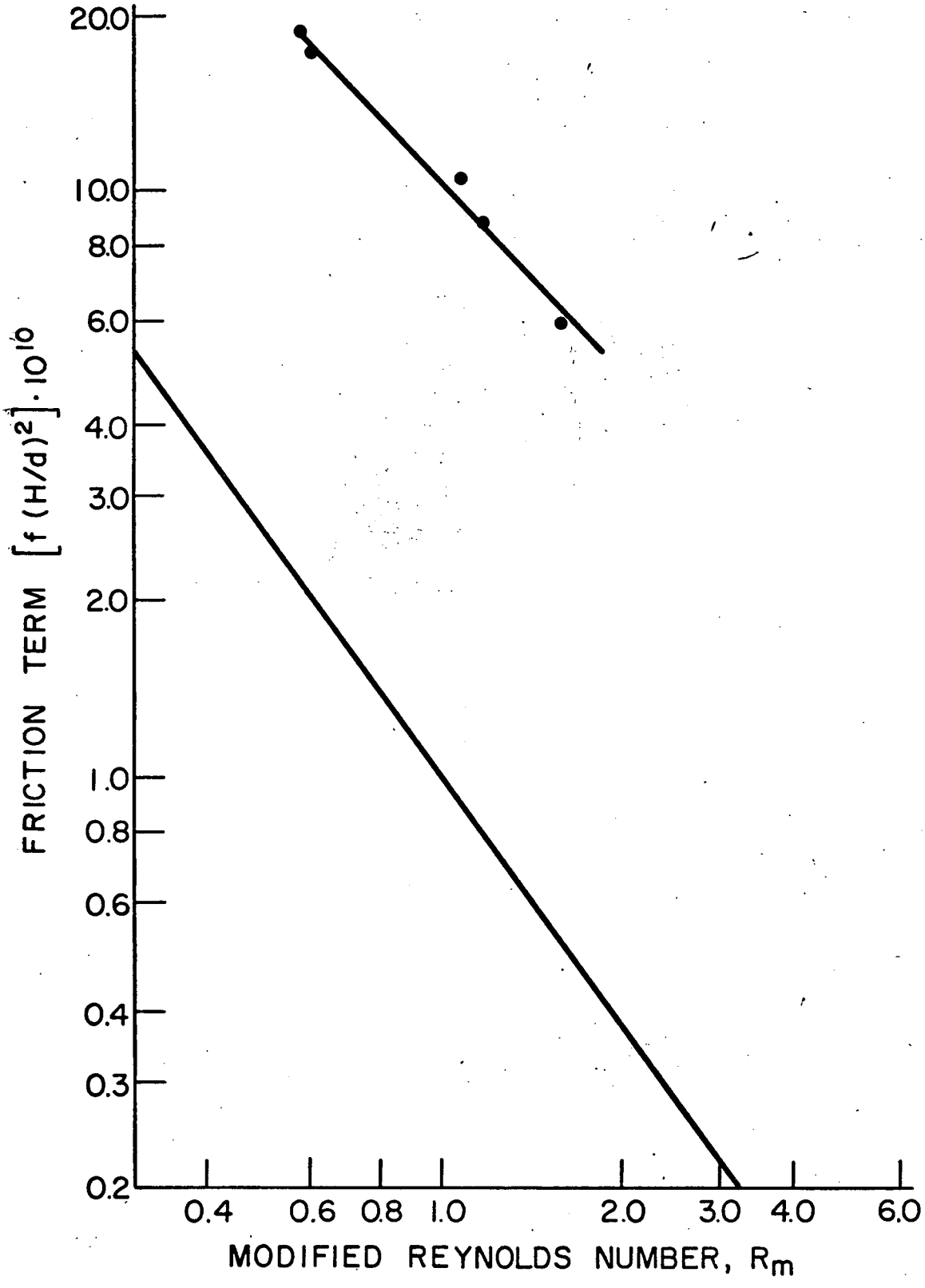

Fig. 15 Headloss Relation

still some points which need attention for trouble-free operation. The following indications are primarily concerned with the operation of PAB pilot units.

Problems during this study occurred primarily with the air supply system. If a compressor is directly connected to the system it should be able to run continuously for several weeks. The preference should be given to a pressure tank system, if possible. In any case there should be a check valve between the units and the air flow control system to keep water from running back into the air lines and control equipment during periods of insufficient air pressures.

The air rates should be kept at a minimum, just high enough to supply sufficient DO and adequate agitation of the bed. This reduces the sloughing action to a minimum and avoids also excessive loss of media. The diffuser should provide a good distribution of air over the column area with a fine bubble size.

Care has to be taken to avoid any obstruction within the bed, especially when the area to depth ratio of the units is relatively small.

6. CONCLUSIONS

The original premise of this study to show the high nitrification effect of the PAB process was not satisfied. Two main factors have prohibited a more intensive investigation which would have revealed more conclusive facts. The limitations of the experimental set-up did not allow the investigation of a wider range of waste and air rates to obtain higher SRT and the relatively high carbonaceous content of

the influent was detrimental to the nitrification process.

This study once more confirmed the excellent performance of the PAB process for organic removal, its flexibility in changes of operation and its essentially troublefree operation. Furthermore, it was shown that it is possible to operate the PAB units with a fine sand media under anaerobic conditions for extended periods of time.

It is the conviction of the author that it will be possible to obtain nitrification in the PAB process when better quality influent is used. Further studies in this direction are necessary.

7. RECOMMENDATIONS AND FUTURE PERSPECTIVES

Any future PAB pilot study for nitrification should be preceded by a careful analysis of the influent particularly with respect to cyanide, heavy metals and other inhibitory material. Effective biological nitrification requires low organic concentration in the range of 40 to 60 mg/l COD with the nitrogen almost completely in inorganic ammonia form. Special attention has to be paid to the possible presence of inhibitors.

The way of providing dissolved oxygen for the microorganisms will need further considerations. Since the PAB process in its present state is essentially a once-through process it is very important, at least for nitrification, to obtain higher organic concentration in the media. Besides investigating media with higher adsorptive capacities,

a careful selection of the diffusors is necessary to produce a fine distribution of air bubbles. Another possibility would be to use pure oxygen which could be supplied at a much lower rate. The decreased agitation of the bed does not seem to be a problem, at least not for fine sand media.

If recirculation is considered, care has to be taken in order to keep sand particles from getting into the recirculation lines. Screens in front of the inlets do not seem to be successful since the fine mesh size required to retain the media particles also retains the organic flocs which results in rapid plugging of the screen. Adequate allowance of the freeboard above the media seems to be the best solution. Increasing the area of the column towards the effluent should provide low enough velocities to keep sand particles from rising to the outlet. Eventually walls with a slight slope might be considered for actual design.

Once good conditions for nitrification in the PAB are established, the process can be further adapted for the denitrification step. The operational conditions of the PAB process are very appropriate for complete nitrogen removal. This study showed the possibility of operating the PAB columns under the anaerobic conditions required for optimum denitrification. Two PAB columns could be put in a sequential operation, the first one aerated to obtain a nitrified effluent and the second one without aeration for denitrification. The sequence could be changed in case extended anaerobic operation results in plugging or excessive expansion of the bed. The high

flexibility of the PAB process would allow such a drastic change of operation without long periods for recovery. The flow scheme of such a potential nitrification - denitrification process is outlined in Fig. 16.

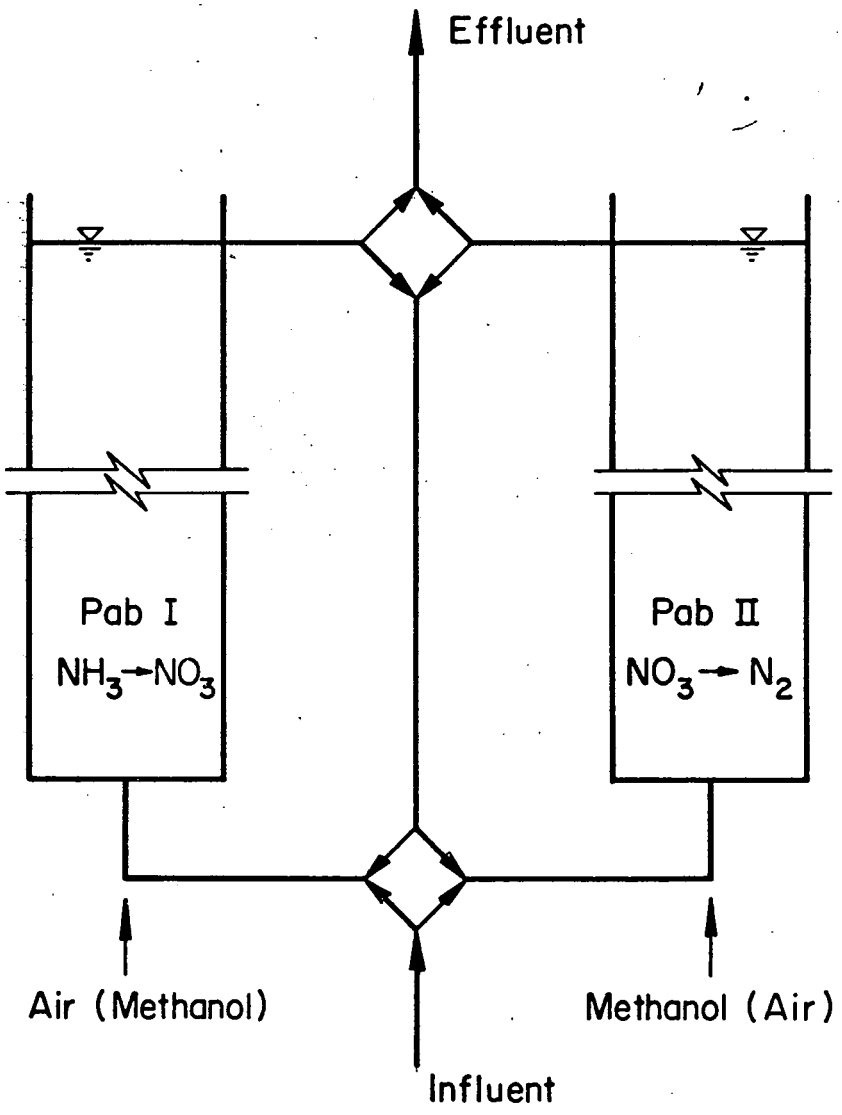

Fig. 16 Flow Diagram for Complete Nitrogen Removal

8. ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the staff of the Bethlehem Sewage Treatment Plant for their financial support and continuous physical assistance, to Mr. Elias Dittbrenner of Fritz Engineering Laboratory, to Ms. Shirley Matlock for the typing of the report, and, last but not least, to Dr. Robert L. Johnson for his help and support throughout this research and the entire studies at Lehigh University.

9. LIST OF FIGURES

10. LIST OF TABLES

11. TERMINOLOGY AND ABBREVIATIONS

ammonium ion	NH_4^+
biochemical oxygen demand, 5-days	BOD_5
bulk concentration	c
chemical oxygen demand	COD
cubicfeet per minute and squarefoot	cfm/sq ft
degree celsius	^oC
dissolved oxygen	DO
excess surface concentration	Γ
foot	ft
friction factor	f
gallons per minute	gpm
gallons per minute and squarefoot	gpm/sq ft
gas constant, universal	R
gramms per day	g/day
horsepower	HP
kinematic viscosity of air	ν_a
kinematic viscosity of water	ν
liter	l
liter per second and squaremeter	$l/sec\text{-}m^2$
media depth	H
milligramms	mg
milligramms per liter	mg/l
millimeter	mm
negative logarithm of hydrogen ion concentration	pH
nitrate ion	NO_3^-

nitrite ion	NO_2^-
particle diameter	d
percent	%
polyvinylchloride	PVC
pounds per cubicfoot and day	lbs/ft^3-day
pounds per squareinch	psi
pulsed adsorption bed	PAB
surface tension	γ
temperature, absolute	θ
total suspended solids	TSS
velocity of air	v_a
volatile suspended solids	VSS

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APPENDIX A: RESULTS OF STAGE 1

A-INFLUENT				B-EFFLUENT PAB 1		C-EFFLUENT PAB 4			
	NITROGEN FORMS			SOLIDS		COD		pH	TEMP.
DATE	NH_4	NO_2	NO_3	TSS	VSS				
	mg/1	mg/1	mg/1	mg/1	mg/1	mg/1	%		°C
10/6/71									
A						114.3		7.15	
B						118.4		7.25	
C						138.7	0	7.30	
10/7/71									
A	24.0	0.35	0.4	31					
B	18.5	0.0	0.1	30					
C	19.8	0.10	0.35	26					
10/8/71									
A	18.8	0.05	0.25	32	26				
B	20.0	0.0	0.15	31	27				
C	21.2	0.0	1.0	26	25				
10/9/71									
A	31.2	0.30	0.0	46	33				
B	21.8	0.15	0.0	44	36				
C	21.8	0.10	0.0	44	32				
10/11/71									
A	24.0	0.45	0.4	37	28			7.65	
B	26.7	0.35	0.35	41	31			7.9	
C	24.0	0.38	0.2	38	27			7.9	
10/12/71									
A	24.0	0.30	0.15	36	26			7.5	
B	24.5	0.25	0.2	40	30			7.7	
C	24.0	0.25	0.2	44	31			7.7	
10/13/71									
A	31.2	0.30	0.25	38	32	143.0			21.0
B	45.0	0.20	0.35	43	35	102.0	29		24.0
C	32.5	0.20	0.15	38	30	110.3	23		24.0
10/14/71									
A	24.8	0.20	0.35	32	25	193.0			
B	24.8	0.10	0.55	39	31	85.8	40		
C	23.8	0.15	0.4	39	24	77.7	46		
10/15/71									
A	40.0	0.30	0.35			122.5		7.45	
B	36.0	0.25	0.25			70.2	43	7.75	
C	32.5	0.05	0.15			83.3	32	7.05	
10/18/71									
A	31.2	0.50	0.5	34	28	131.4		7.7	
B	50.0	0.50	0.35	33	25	100.8	23	7.9	
C	32.5	0.30	0.5	26	20	109.5	17	7.8	
10/19/71									
A	25.0	0.35	0.0	25	17	149.0		7.6	
B	36.5	0.25	0.0	31	28	100.8	32	7.8	
C	39.3	0.05	0.0	31	28	114.0	23.5	7.65	
AVERAGE									
A	27.42	0.31	0.265			137.78		7.58	
B	30.38	0.205	0.23			91.92	33.4	7.81	
C	26.64	0.158	0.295			98.96	28.3	7.74	

APPENDIX B: RESULTS OF STAGE 2

A-INFLUENT				B-EFFLUENT PAB 1				C-EFFLUENT PAB 4	
	NITROGEN FORMS			SOLIDS		COD		pH	TEMP.
DATE	NO_4	NO_2	NO_3	TSS	VSS				
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	%		°C
10/20/71									
A	24.0	0.38	0.5	26	26	127.0		7.6	
B	34.3	0.0	0.4	22	22	87.6	31	7.8	
C	32.5	0.05	0.95	24	22	127.0	0	7.7	
10/21/71									
A	37.5	0.40	0.35	25	25	127.2		7.4	
B	41.0	0.15	0.25	49	42	118.8	6.5	7.5	
C	39.0	0.20	0.0	34	28	127.2	0	7.5	
10/22/71									
A	22.8	0.43	0.15	34	27	118.8		7.4	
B	24.5	0.20	0.0	22	19	84.8	28.5	7.5	
C	25.3	0.05	0.1	24	20	106.0	11	7.5	
10/25/71									
A	22.8	0.55	0.35	31	26	97.5		7.5	
B	22.8	0.20	0.0	23	23	76.3	21.5	7.6	
C	23.5	0.35	0.2	19	18	80.6	17	7.6	
10/26/71									
A	22.8	0.40	0.2	31	26	89.0			21.0
B	24.0	0.0	0.0	25	21	55.2	38		24.0
C	22.5	0.0	0.0	26	21				23.5
10/27/71									
A				31	25	99.4			
B				22	19				
C				26	22	76.8	22.5		
10/28/71									
A	21.5	0.45	0.35	33		131.0			
B	22.5	0.15	0.25	23		99.4	24		
C	22.8	0.15	0.20	24		117.4	10		
10/29/71									
A	23.3	0.38	0.90	29	24	131.0			
B	22.3	0.0	0.40	22	21	99.4	24		
C	22.3	0.10	0.25	22	19	113.0	13.5		
11/1/71									
A	23.5	0.63	0.65	32	26	108.6			
B	23.3	0.15	0.35	24	20	99.6	8		
C	24.0	0.30	0.40	31	24	100.1	7.5		
AVERAGE									
A	24.78	0.45	0.43			114.39		7.475	
B	26.84	0.11	0.21			90.13	22.69	7.6	
C	26.49	0.15	0.26			106.01	10.19	7.575	

APPENDIX C: RESULTS OF STAGE 3

A-INFLUENT				B-EFFLUENT PAB 1					C-EFFLUENT PAB 4		
DATE	NH_4^+ mg/l	NO_2^- mg/l	NO_3^- mg/l	TSS mg/l	VSS mg/l	COD mg/l		pH	TEMP. ^oC	HEAD LOSS psi	SRT days
11/3/71											
A	18.3	0.5	0.40	27	21	75.7					
B	17.8	0.85	0.40	30	20	70.3	11				
C	17.5	0.25	0.15	16	13	70.3	11				
11/4/71											
A	21.2	0.43	0.35	36	29	130.0					
B	21.2	0.20	0.25	25	21	78.9	39				
C	19.7	0.20	0.0	20	18	88.3	32				
11/5/71											
A	21.7	0.45	0.65	39	30	153.2					
B	22.3	0.15	0.25	30	24	106.8	30				
C	22.0	0.05	0.95	30	25	102.2	33.5				
11/8/71											
A	24.0	0.38	0.40	30	25	116.6			17.0		
B	25.3	0.30	0.0	34	25	92.9	20		21.0		
C	25.7	0.30	0.10	31	23	78.9	32		21.0		
11/9/71											
A	21.2	0.25	0.25	32	28	108.2					
B	20.3	0.10	0.0	41	35	70.8	34.5				
C	21.3	0.10	0.0	40	31	66.7	38.5				
11/10/71											
A	20.7	0.30	0.40	42	33	141.5		7.85			
B	22.0	0.63	0.20	31	27	82.4	42	7.95			
C	20.0	0.63	0.0	27	25	99.9	29	7.9			
11/11/71											
A	22.3	0.50	0.10	26	21	141.5		7.5			
B	22.3	0.20	0.65	25	21	99.9	29	7.6			
C	22.5	0.20	0.65	26	20	95.8	32	7.55			
11/12/71											
A	18.8	0.25	0.60	30	26	81.0			17.0		
B	20.3	0.0	0.0	28	24	68.8	15		21.5		
C	19.4	0.05	0.35	95	49	72.0	11		21.5		
11/16/71											
A	11.0	0.53	0.10	26	21	141.5					
B	13.0	0.28	0.16	30	22	93.0	34.5			7.0	
C	12.6	0.13	0.14	23	17	105.2	25.5			7.0	
11/17/71											
A	17.75	0.25		47	42	129.3					
B	17.25	0.13		34	29	89.0	31				
C	19.0	0.10		32	26	105.1	19				
11/18/71											
A	17.0	0.38	0.15	24	22	145.4		7.25			
B	16.1	0.18	0.07	29	24	101.0	30.5	7.35			
C	16.1	0.12	0.10	20	20	101.0	30.5	7.35			

APPENDIX C (continued)

DATE	NH_4^+ mg/l	NO_2^- mg/l	NO_3^- mg/l	TSS mg/l	VSS mg/l	COD mg/l		pH	TEMP. ^oC	HEAD LOSS psi	SRT days
11/19/71											
A	18.25	0.40	0.26	21	17	108.0			17.5		
B	18.25	0.14	0.16	26	21	76.1	29.5		21.0		
C	17.75	0.12	0.15	23	20	88.1	18.5		21.0		
11/22/71											
A	21.5	0.68	0.72	23	19	116.0		7.25			
B	22.0	0.61	0.44	28	22	72.1	38	7.3			
C	22.5	0.37	0.29	22	17	72.1	38	7.3			
11/23/71											
A	17.0	0.17	0.36	29	26	160.0		7.15			
B	17.0	0.33	0.22	40	37	88.1	45	7.25			
C	17.5	0.53	0.16	27	25	108.0	32.5	7.25			
11/29/71											
A	21.5	0.68	0.80	27	20	160.0					
B	21.5	0.65	0.59	26	19	96.1	40				1.7
C	22.3	0.40	0.36	28	21	96.1	40				3.3
AVERAGE											
A	19.48	0.41	0.40			127.0		7.4			
B	19.77	0.28	0.24			85.6	31.3	7.49			
C	19.72	0.24	0.24			89.7	28.0	7.47			

APPENDIX D: RESULTS OF STAGE 4

A-INFLUENT				B-EFFLUENT PAB 1					C-EFFLUENT PAB 4		
DATE	NH_4^+	NO_2^-	NO_3^-	TSS	VSS	COD		pH	TEMP.	HEAD LOSS	SRT
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	%		°C	psi	days
12/1/71											
A	12.3			19	17						
B	12.7			23	20						
C	12.7			25	19						
12/2/71											
A	15.0	0.56	0.52	30	26	104.1			14.0		
B	15.5	0.61	0.34	37	24	56.1	46		20.5	6.0	
C	15.5	0.64	0.30	23	17				19.5	7.0	
12/3/71											
A	16.0	0.48	0.46	31	25	121.2					
B	15.75	0.53	0.25	25	23						
C	17.25	0.37	0.24	22	18	78.2	37.5				
12/6/71											
A	20.0	0.57	0.58	26	23	147.5					
B	19.5	0.62	0.44	23	20	82.0	44.5				
C	20.3	0.47	0.35	26	21	94.3	36				
12/7/71											
A	15.3	0.47	0.46	43	35	69.7					
B	16.5	0.50	0.32	14	12	45.2	35			6.5	5.15
C	16.3	0.34	0.24	27	22	49.2	29.5			6.5	2.9
12/8/71											
A	16.3	0.50	0.40	33	27	151.6					
B	16.3	0.49	0.28	23	20	73.8	51				
C	16.3	0.33	0.20	23	21	98.4	35				
AVERAGE											
A	15.8	0.52	0.48			119.7					
B	15.4	0.55	0.33			64.28	44.2				
C	15.7	0.43	0.27			80.03	34.6				

APPENDIX E: RESULTS OF STAGE 5

A-INFLUENT				B-EFFLUENT PAB 1					C-EFFLUENT PAB 4		
DATE	NH_4^+	NO_2^-	NO_3^-	TSS	VSS	COD	%	pH	TEMP.	HEAD LOSS	SRT
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l			°C	psi	days
12/22/71											
A	16.5	0.28	0.25	49	39	207.0		7.8			
B	15.0	0.22	0.38	137	79	156.5	24.5	7.95			
12/23/71											
A	17.5	0.02	0.13	30	25	110.0					
B	17.0	0.07	0.13	31	24	76.2	31				0.74
12/24/71											
A	17.25	0.0	0.10	18	16						
B	17.0	0.02	0.14	43	31						
12/27/71											
A	22.25	0.27	0.25	59	45	308.5			14.5		
B	21.5	0.05	0.18	43	34	156.4	49		21.5	7.0	0.75
12/28/71											
A	18.75	0.15	0.19	44	36	193.5					
B	18.75	0.07	0.16	39	32	107.2	44.5				1.1
12/29/71											
A	20.9	0.34	0.22	41		185.3					
B	20.1	0.15	0.18	45		131.8	29				
12/30/71											
A	20.9	0.33	0.26	39		173.0					
B	20.25	0.07	0.21	45		131.8	24				
1/3/72											
A	17.3	0.62	0.64	41	41	144.0		7.6	14.0		
B	19.6	0.35	0.22	25	25	81.7	43.5	7.65	20		2.3
1/4/71											
A	17.8	0.39	0.30	42	36	194.5		7.7			
B	17.3	0.08	0.18	43	35	132.2	32	7.8			
C	17.3	0.07	0.14			143.9	26	7.6		10.7	2.1
1/6/72											
A	16.6	0.50	0.38	25	24	132.2		7.85	13.0		
B	15.3	0.12	0.15	25	22	81.7	38	7.9	21	7.7	3.0
AVERAGE											
A	18.58	0.29	0.27			183.0		7.74			
B	18.18	0.12	0.19			117.28	35	7.83			

14. ABOUT THE AUTHOR

Karl Georg Doutlik was born on November 8, 1945 in Radstadt, Austria. He grew up in Vienna, Austria, where he also attended high school. He graduated 1963 as second of his class.

He attended college at the Hochschule fuer Bodenkultur in Vienna from 1964 to 1970, where he received the degree Diplom-Ingenieur on June 12, 1970.

He was presented a Graduate Fellowship by the Rotary Foundation of Rotary International for the academic year 1970/71. With this fellowship he started graduate work at Lehigh University.

He plans to remain in the United States for practical training before returning to Europe.